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EFFECT OF PARALLEL MIDBODY ON THE RESISTANCE OF SHIPS IN LEVEL ICE

TP 9242E

For

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17. Abstract

This report presents the results of an investigation of the influence of parallel midbody length on resistance in ice, and how this is affected by the friction coefficient and by two different bow forms.

Model tests were conducted at the ice tank of the Institute for Marine Dynamics (IMD) in St. John's, Newfoundland. The models were built up of 11 parts; six bows, four midbodies and one stern. The basic model is a 1:30 scale reproduction of the ARCTIC. The tests consisted of 12 towed resistance tests in model EG/AD ice representative of 0.9 m, 1.2 m and 1.5 m, 570 kPa full scale ice. The results and findings may be summarized as:

a) The influence of the midbody length varies with the bow form, and the model speed.

b) The high friction coefficient test yielded a higher speed dependency than would have been anticipated.

This work resulted in a number of recommendations which related to; (a) the need for a reliable way to index the ice characteristics, (b) the need to run several additional ice sheets and, (c) a review of all the previous IMD ice sheets to obtain data on ice sheet consistency.

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17. Résumé

Ce rapport donne les résultats de la recherche sur l'influence de la longueur de la section médiane rectangulaire de l'ARCTIC sur la résistance à l'avancement des glaces, en fonction de la géométrie de proue et du coefficient de frottement.

Des essais sur maquettes ont eu lieu dans le bassin des glaces de l'Institut de dynamique marine (IDM) à St. John's, Terre-Neuve. Pour l'assemblage des maquettes représentant l'ARCTIC au 1/30, un total de onze sections séparées ont été fabriquées, soit six proues, quatre sections médianes rectangulaires et une poupe. Il y a eu en tout douze essais de résistance à l'avancement dans une glace modèle EG/AD d'épaisseur et de résistance correspondant à des glaces réelles de 0,9, 1,2 et 1,5 m et 570 kPa. Les résultats peuvent être résumés comme suit:

a) L'influence de la longueur de la section médiane rectangulaire de la coque sur la résistance à l'avancement varie selon la géométrie de la proue, la vitesse d'avancement.

b) L'essai de résistance avec un coefficient de frottement élevé a montré que la sensibilité au facteur vitesse est beaucoup plus prononcée que prévu.

Des recommandations ont été formulées concernant: a) le besoin d'un dispositif fiable pour contrôler les caractéristiques des glaces, b) le besoin de plus amples essais de résistance et c) un examen de toutes les couches de glaces modèles fabriquées par l'IDM afin d'en déterminer les caractéristiques communes.

18. Mots-clés	19. Diffusion
Section médiane rectangulaire, coefficient de frottement, résistance, déglaçage, essais sur maquettes.	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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SUMMARY

The MV Arctic was built in 1978 as a 28,000 DWT bulk carrier, classed to Arctic Class 2 of the Canadian Arctic Shipping Pollution Prevention Regulations (CASPPR), and upgraded to an equivalent CASPPR Class 4 notation in the winter of 1985/86. The upgrade included the construction of a new bow, and the subsequent full scale trials showed a significant improvement in icebreaking capability.

One explanation for this improvement was the breaking action of the new bow which tended to break a wider channel than the original hull form and, as a result, reduced the contact between the ship's parallel midbody and the ice. This report investigates the influence of parallel midbody length on resistance and how this is affected by friction coefficient and by two different bow forms; the original ARCTIC bow and the new bow (Melville bow).

The model tests were conducted at the ice tank of the Institute for Marine Dynamics (IMD) in St. John's, Newfoundland. The models were built up from 11 parts; six bows (three Melville bows and three original bows), four midbodies (two whole midbodies and two part midbodies), and one stern. The basic model is a 1:30 scale reproduction of the ARCTIC, and each part was prepared with a specific surface friction coefficient. The model tests consisted of 12 towed resistance tests in model EG/AD ice representative of 0.9 m, 1.2 m and 1.5 m 570 kPa full scale ice. These ice thicknesses and strengths correspond to 30 mm, 40 mm and 50 mm, 19 kPa model ice.

The model test program was conducted during January and February of 1988, using standard model test procedures.

There were a number of anomalies in the test program and a significant effort was made to generate reliable data. To some extent this was successful but it should be noted that, in some areas, the results are not considered by Melville to be representative of the actual relationships.

The primary conclusions to this test program may be summarized as follows:

a) The influence of the midbody length on the resistance of icebreakers varies with the bow form and the ship speed. In the case of the Melville bow at a low speed, a 20 percent increase or decrease in ship length results in about a 5 percent change in resistance. At higher speeds a similar increase or decrease in length results in an 18 and 12 percent change in resistance respectively. The results from the original bow are inconclusive.

b) The sensitivity of resistance to speed increases significantly with increasing friction coefficient. Indeed, the high friction coefficient test yielded a significantly higher speed dependency than would have been anticipated.

c) Manipulating the scale to yield a prototype ship with a displacement 20 percent higher and 20 percent lower than the original ship resulted in about a 4 to 7 percent change in resistance respectively.

d) Manipulating the scale to a prototype ship of the same displacement indicated that higher length to breadth ratio ships tend to have lower resistances. No real maximum or minimum values were found in this analysis.

The model test study and associated analysis described in this report resulted in a number of recommendations. These may be summarized as follows:

a) The need to evaluate and monitor ice strength has been highlighted as a major concern to the model ice experimenter. The development and interpretation of an Indexer that can be used to monitor and calibrate an ice sheet along its entire length should form a high priority.

b) A number of the ice sheets yielded unusual resistance data. To validate the results of this program, it is recommended that additional model tests be conducted. These are:

   i) High friction coefficient on the Melville bow form.

   ii) Thin ice resistance for the Melville bow.

   iii) Additional model tests in 1.85 m ice from which a comparison may be made to the full scale data.

   iv) The original bow should be re-tested with the ship's original length.

c) Additional ice tests should be conducted with very low ice strengths, for example, 5 to 10 kPa.

The IMD have now completed over 200 ice sheets. It is considered that a major benefit would accrue from a detailed review of this data. This would include a description of the ice formation process and the parameters that influence the ice growth, together with a statistical analysis of the ice mechanical properties and the influence of each variable on the resultant ice properties.

SOMMAIRE

Le N.M. ARCTIC construit en 1978 est un vraquier de 28,000 tonnes de port en lourd, de cote arctique 2 aux termes de la Loi canadienne sur la prévention de la pollution dans les eaux arctiques. Durant la saison d'hiver 1985-1986, cette cote a été relevée à 4 lorsque l'ARCTIC a reçu une nouvelle proue et après que les essais auxquels il a été soumis eurent montre des performances supérieures dans les glaces.

Cette amélioration s'explique en partie par l'action brisante de la nouvelle proue qui ouvre dans la glace un chenal plus large que l'ancien, avec la conséquence que le frottement entre la section médiane rectangulaire de la coque et les glaces a diminué. Par la recherche, on a voulu établir le rapport que pouvait exister entre la longueur de cette section et la résistance a l'avancement, et l'influence que pourraient avoir le coefficient de frottement, et le remplacement de l'ancienne proue par une nouvelle (proue Melville).

Les essais sur maquettes ont eu lieu dans le bassin des glaces de l'Institut de dynamique marine (IDM) à St. John's, Terre-Neuve. Pour l'assemblage des maquettes, onze sections au total ont été fabriquées, soit six proues (trois nouvelles et trois anciennes), quatre sections médianes rectangulaires (deux pleine longueur de deux demi-longueur) et une poupe. La maquette était a l'échelle 1/30 du N.M. ARCTIC et chaque partie avait été fabriquée dans un materiau ayant un coefficient de frottement différent. Il y a eu en tout douze essais de résistance à l'avancement dans une glace modèle EG/AD de 30, 40 et 50 mm d'épaisseur et d'une résistance de 19 kPa, ce qui correspond à des glaces réelles de 0,9, 1,2 et 1,5 m d'epaisseur et a une resistance de 570 kPa.

Les essais sur maquettes ont été exécutés en janvier et février 1988 suivant les procédures standard.

Un certain nombre d'anomalies ont été constatées a l'issue de programme, mais on s'est efforcé néanmoins d'en tirer des résultats fiables. Malgré cela, le contractant, Melville, estime que, dans certains secteurs, les résultats ne représentent pas fidelèment les relations qui jouent dans la réalité.

Les principales conclusions peuvent être resumées comme suit:

a) L'influence de la longueur de la section médiane rectangulaire de la coque sur la résistance à l'avancement varie selon la géométrie de la proue et la vitesse d'avancement. Avec la nouvelle proue et a faible vitesse, une variation de 20 p. 100 en plus et en moins de la longueur totale réduit la résistance de quelque 5 p. 100. Aux vitesses plus élèvées, une variation de même ordre en plus et en moins dans la longueur produit en changement de 18 et 12 p. 100, respectivement.

b) La sensibilté de la résistance au facteur vitesse est étroitement liée a l'augmentation de coefficient de frottement. En fait, à un coefficient de frottement élevé, cette sensibilité a été beaucoup plus

prononcée que prévu. Mais elle ne se manifeste que lorsque la proue et la section médiane rectangulaire sont toute deux caracterisées par un coefficient de frottement élevé.

c) En maintenant la similitude avec un navire hypothètique ayant un déplacement que varie de l'ordre de 20 p. 100 en plus et en moins, le changement correspondant dans la résistance a été d'environ 4 et 7 p. 100, respectivement.

d) A déplacement égal, la résistance tend à diminuer à mesure que le rapport longueur/largeur de coque croît. L'analyse n'a cependant pas mis en évidence des valeurs maximums ou minimums réelles.

Les essais sur maquettes et la recherche analytique subséquente décrits dans le rapport ont permis de déboucher sur un certain nombre de recommandations qui peuvent être résumées comme suit:

a) Le mesurage et le suivi de la résistance mécanique des glaces sont considérés comme des opérations necéssaires, interessant fortement les chercheurs. La mise au point et l'utilisation correcte d'un Indexer permettant de caractériser une glace modèle et de l'étalonner sur toute sa longueur serait un atout du plus grand intérêt.

b) Certaines couches de glaces ont dégagé des valeurs de résistance inusitées. Pour que les résultats de programme puissent être valides, de plus amples essais de résistance seront nécessaires, faisant intervenir les variations suivantes:

   i) essais à coefficient de frottement élevé et avec la nouvelle proue;

   ii) essais avec la nouvelle proue dans une glace peu épaisse;

   iii) essais de résistance a l'avancement dans une glace modele equivalant à une épaisseur de 1,85 m aux fins de comparaison avec les essais en vraie grandeur;

   iv) essais avec l'ancienne proue et une section médiane rectangulaire pleine longueur.

c) Essais de résistance à l'avancement dans des glaces de très faible résistance, de 5 a 10 kPa, par example.

À ce jour, l'IDM a effectué des essais dans plus de 200 couches de glace modèle. Il serait donc d'un grand intérêt de pouvoir passer en revue les résultats de ces essais, d'avoir une description du procédé de fabrication de cette glace, de connaître les parametres relatifs à la croissance des cristaux et, enfin, d'effectuer une analyse statistique des propriétés mecaniques de cette glace pour déterminer l'influence de chacune des variables sur elles.

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1. INTRODUCTION

The MV ARCTIC was built in 1978 as a 28,000 DWT bulk carrier, classed to the Canadian Arctic Shipping Pollution Prevention Regulations (CASPPR) Class 2. Following extensive redesign and construction, the ship was converted to an OBO (OIL/BULK/ORE) carrier in the winter of 1984/85 and upgraded to an equivalent CASPPR Class 4 notation in the winter of 1985/86. The upgrade to equivalent CASPPR Class 4 included the construction of a new bow. The new bow, known as the Melville bow, was designed and model tested in three different ice tanks during 1982 to 1984 and, after construction, was full scale tested in the spring of 1986. The full scale trials demonstrated a significant improvement in the ship's icebreaking capability.

One explanation for this improvement was the breaking action of the new bow which tended to break a wider channel than the original hull form and, as a result, reduced the contact between the ship's parallel midbody and the ice. Two model test programs were undertaken to investigate this phenomenon in more detail. The first program reviewed the influence of the friction coefficient on the bow and midbody (Melville 1987). This is referred to in the remainder of this report as the "FRICTION" program. This report describes the second program, referred to as the "MIDBODY" program, which investigates the influence of parallel midbody length on resistance and how this is affected by friction coefficient and two different bow forms, represented by the Original ARCTIC bow and the Melville bow.

The ARCTIC is designed to be capable of operating in the Great Lakes and, as a result, has a relatively high length to beam ratio (L/B). This is unusual in comparison with other icebreakers which tend to have significantly lower L/B ratios. To investigate the effect of this ratio on the icebreaking resistance in more detail, a series of model tests were completed.

Extensive model tests have already been undertaken on the ARCTIC based on a 1:30 scale model. The model was built in three sections, a bow, midbody and stern. This division of the model permitted the length variation parameter to be studied by removing or adding to the existing midbody section. This was accomplished with minimal additional work and avoided the need to build new models for the test program.

The influence of the length variation on resistance may also be affected by the bow form and friction coefficient of the model. To investigate these effects the model tests included the Original and Melville bows fitted to the ARCTIC and three different friction coefficients.

The report is divided into three sections. The first section describes the model test and reviews the data collection procedures. The second section describes the analysis of the relationships between resistance and ice property variables and derives the correction procedure. The third section presents the relationship between resistance and the hull form variables as functions of displacement and friction coefficient.

2. MODEL TESTS

2.1 General

The model tests were conducted at the ice tank of the Institute for Marine Dynamics (IMD) in St. John's, Newfoundland. Details of the ice tank and the facility have been published in the literature {Jones 1987}. The models were built up from 11 parts; six bows (three Melville bows and three Original bows), four midbodies (two whole midbodies and two part midbodies), and one stern. The basic model is a 1:30 scale reproduction of the ARCTIC. Each part was prepared with a specific surface preparation defined in a later section of this report. With the exception of the stern, which was made of wood, the models were constructed from fibreglass, reinforced with wooden frames. This is now a standard model fabrication technique used at the IMD.

The model tests consisted of 12 towed resistance tests in model EG/AD ice {Timco 1985} representative of 0.9 m, 570 kPa full scale ice. Additional tests were also conducted in equivalent 1.2 m and 1.5 m ice sheets to investigate the effect of ice thickness on resistance and to compare the results with previous model tests {Melville 1985 and Melville 1984}. These ice thicknesses and strengths correspond to 30 mm, 40 mm and 50 mm, 19 kPa model ice. The ice strength is higher than would have been preferred but is commonly selected in this way to ensure consistent strength, which is difficult to obtain with weaker ice.

2.2 Model Test Program and Test Plan

The test program was conducted to investigate the influence of ice thickness, midbody length, bow form and friction coefficient on the resistance of an icebreaker. Table 2.1 presents the scope of the test program and the combinations of ice thickness, hull lengths, bow forms and friction coefficient. The scope may be summarized as;

a) Ice thickness variation at a friction coefficient of 0.06 for the Melville bow on the existing ship length. These are represented by ice sheets 1, 2 and 3.

b) Three length variations for the Melville bow and two for the Original bow based on both bows at a friction coefficient of about 0.06. These are represented by ice sheets 3, 7, 13 and 14 for the Melville bow and ice sheets 10, 11 and 12 for the Original bow.

c) Three friction coefficients based on a short ship. These are represented by ice sheets 5, 7 and 8 for the Melville bow and ice sheets 6, 9 and 10 for the Original bow.

d) A high friction test of the existing ARCTIC fitted with the Melville bow. This is represented by ice sheet 4.

TABLE 2.1

PARALLEL MIDBODY PROJECT

MODEL TEST PROGRAM MATRIX

MOLEL PART FRICTION	MELVILLE BOW 0.33	0.06	0.004	ORIGINAL BOW 0.33	0.06	0.004	SHORT MIDBODY 0.33	0.06	WHOLE MIDBODY 0.33	0.06	STERN 0.1	COMMENTS
Ice Sheet #1		*								*	*	h = 50 mm
Ice Sheet #2		*								*	*	h = 40 mm
Ice Sheet #3		*								*	*	h = 30 mm
Ice Sheet #4	*								*		*	h = 50 mm
Ice Sheet #5	*										*	h = 30 mm
Ice Sheet #6				*							*	h = 30 mm
Ice Sheet #7		*									*	h = 30 mm
Ice Sheet #8			*								*	h = 30 mm
Ice Sheet #9						*					*	h = 30 mm
Ice Sheet #10					*						*	h = 30 mm
Ice Sheet #11					*						*	h = 30 mm
Ice Sheet #12					*					*	*	h = 30 mm
Ice Sheet #13		*						*		*	*	h = 30 mm
Ice Sheet #14		*						*			*	h = 30 mm

The model test program was conducted during January and February of 1988, using standard test procedures that may be summarized as follows;

- ice flexural strength and elastic modulus recorded prior to the model test,
- continuous model tests down the center of the tank at five target speeds: 0.02, 0.19, 0.33, 0.47 and 0.6 m/sec corresponding to 0.1, 1, 1.8, 2.5 and 3.3 m/sec at full scale,
- ice sheet thickness and flexural strength measurements,
- preparation for the presawn ice tests consisting of "stapling" the existing broken ice sheet and floe cutting,
- presawn ice test at the same speeds as the first set of tests down the south side of the ice tank, parallel to the first test run, and
- flexural strength measurements.

Details of each test and associated procedure is given in the test plan, presented in Appendix A. The IMD report from the model tests forms Appendix B. The measured mechanical and physical properties of the ice sheet are presented in Appendix D and the model condition in Appendix E.

In addition to the standard model test procedures, each test was followed by an Indexer run. The Indexer is a device, developed by Melville in association with IMD and TDC, that is designed to measure the mechanical properties of a model ice sheet throughout its length, simultaneously with the model test {Baker 1986}. The device is currently under development and was used in this project to assist in the selection of the test windows for data averaging. It is hoped that additional development work will permit better correlation with conventional model ice testing procedures and the interpretation of the Indexer output to permit more accurate model scaling.

2.3 Model Test Results

2.3.1 Data Overview

A total of 14 ice sheets were tested with target thicknesses of 30 mm, 40 mm and 50 mm and a target strength of 19 kPa. Appendix F presents the uncorrected data recorded from the test series. The data is extracted from Melville's standard model test analysis program: the first four columns define the ice sheet number, measured ice thickness, strength and model speed. The fifth column presents the resistance data and includes any corrections that may have been applied. Any correction applied is shown in the sixth column. The seventh column is the model identifier used in the program. The model identifier defines the friction coefficient used on the bow, midbody and stern, together with the type of bow, length of midbody and model ice thickness.

For example 0.06 MB/0.06 PM 1.7/S/30 designates respectively: a 0.06 friction coefficient on the Melville Bow (MB), the Original bow is designated OB; a 0.06 friction coefficient on the Parallel Midbody (PM), equal to 1.7 times the base case length; a stern (S), which was constant and hence does not have any other designation, and; tests completed in 30 mm ice.

It can be seen from the data in Appendix D that the ice thicknesses were achieved to within about 2 mm of target values. This margin of less than 10 percent is considered to be well within the current ice testing standards. The ice strength variation across the test program was considerable higher and ranged from 10.9 to 28.4 kPa. These average values are calculated from sets of four cantilever beam tests, individual ice strengths were recorded as low as 8 kPa. This range of ice strength is not within the currently acceptable standards for model ice testing and, as a result, those ice tests that were associated with the low strengths have been assessed in more detail.

The problem with data collected from ice sheets with low strength properties is the validity of scaling the resistance from the low strength value to the target values at which the comparisons of ship configuration are made.

During 1986/87, Melville was involved in an extensive series of tests to investigate the effect of model surface friction on resistance (Melville 1987). Two of the tests conducted as part of this friction program were repeated as part of the midbody tests. This offers an opportunity to compare the low strength tests of the midbody program with tests conducted at target ice strength and thickness in the friction program.

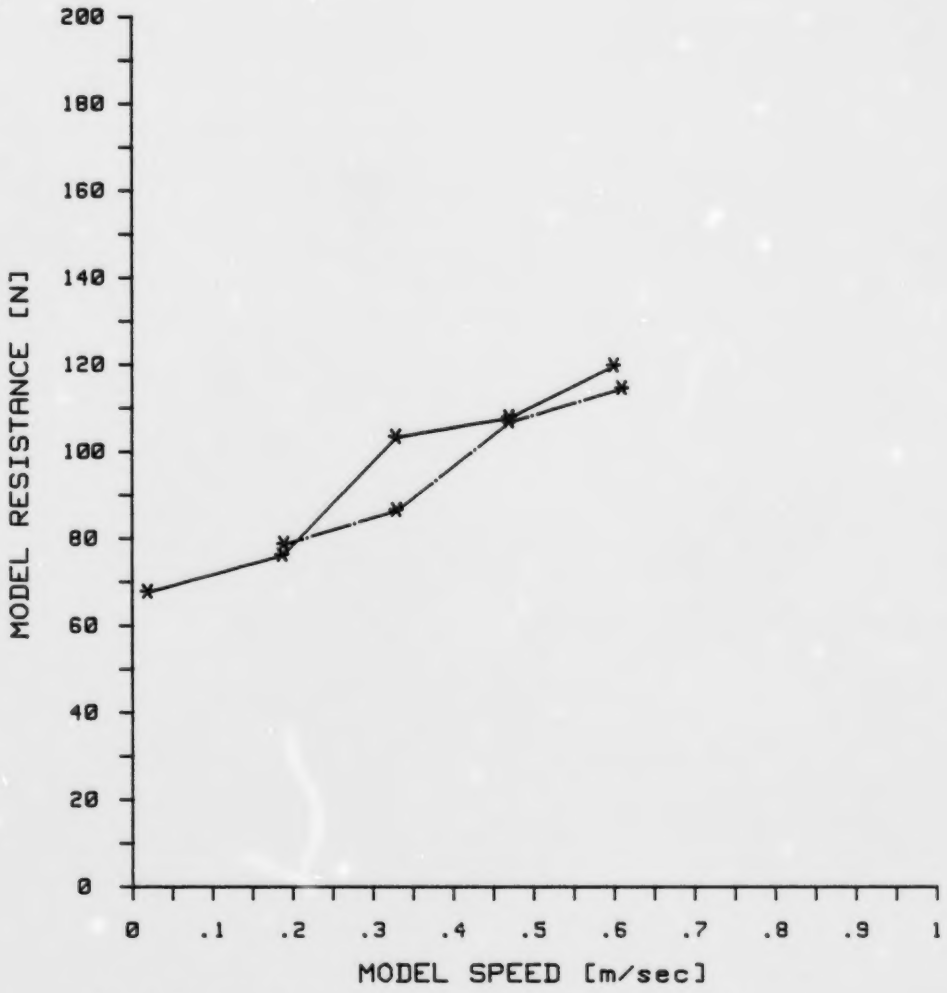
Figure 2.1 presents a comparison between the test results of the model of the existing ship, in 50 mm ice, in the midbody and friction test programs. The data, which was not associated with large ice thickness or strength deviations from target values, has been adjusted to target strength and thickness using the standard procedures described below. The total resistance for each test, across the speed range, varies from under 5 percent to a maximum of 16 percent for the 0.33 m/sec test. This is considered to be a good correlation between these two tests.

Figure 2.2 presents the correlation between uncorrected data from the friction and midbody test programs for the 40 mm ice sheets. Test ice strength for the friction program was 17 kPa, and for the midbody program ranged from 10.9 to 17.5 kPa. It may be seen from this figure that, although the midbody data is associated with weaker ice, it records a higher resistance than the friction test data. The only two speeds at which the data sets correlate is 0.6 m/sec, which corresponds to the 17.5 kPa data point from the midbody program, and the 0.2 m/sec data point, which is associated with 10 kPa in the midbody program and 17 kPa in the friction program.

The comparison between these two tests would indicate that the variation of resistance with strength may not be a linearly increasing relationship but may exhibit an inflection at low strengths where resistance may not increase with strength.

FIGURE 2.1

CORRECTED RESISTANCE vs SPEED FROM THE FRICTION AND MIDBODY TEST PROGRAMS FOR THE MELVILLE BOW



Midbody test program ; Ice sheet #1
Friction test program ; Ice sheet #1
Data corrected to target strength and thickness
Target ice thickness = 0.05 m
Target ice strength = 500 kPa
Friction coefficient = 0.06
Midbody program = Solid line
Friction program = Broken line

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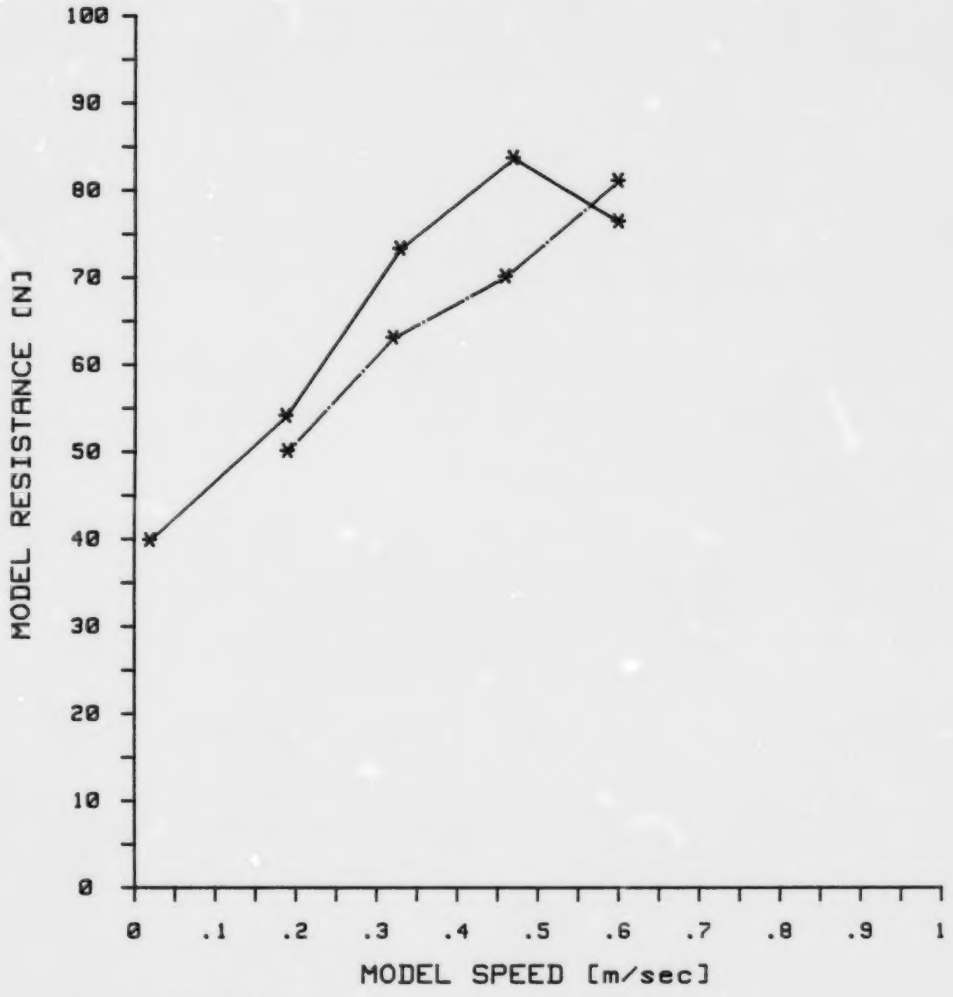
FIGURE 2.2

UNCORRECTED RESISTANCE vs SPEED FROM THE FRICTION AND MIDBODY TEST PROGRAMS FOR THE MELVILLE BOW



Midbody test program ; Ice sheet #2
Friction test program ; Ice sheet #2
Data un-corrected for thickness or strength
Target ice thickness = 0.04 m
Target ice strength = 19 kPa
Friction coefficient = 0.06
Midbody program = Solid line
Friction program = Broken line

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Model tests conducted by Melville in the last few years have shown that ice strengths down to about 15 or 16 kPa are acceptable and exhibit the same relationships between resistance and strength as at higher strengths. Data points, and to some extent the ice sheet as a whole, associated with lower values have been specially analysed since, at the present time, there is no standard procedure for correcting the resistance for these low strength values.

During the program there were seven ice sheets that contained tests with flexural strengths of less than 15 kPa. Based on the average of several individual strength measurements in each designated test area. These ice sheets were:

Ice Sheet #2 Three data points below 15 kPa, 10.9, 13.6 and 13.4 kPa. The data points tend to yield higher resistances than an identical test, conducted as part of the friction test program, at a higher strength.

Ice Sheet #3 Two data points below 15 kPa, 11.1 kPa and 13.5 kPa. The 11.1 kPa resistance data point is higher than would be anticipated, the 13.5 kPa appears to be consistent with the higher speed 15.8 and 17.2 kPa data points

Ice Sheet #7 One data point below 15 kPa, 13 kPa, which yields (after conventional correction) a higher resistance value than the higher speed 20.8 kPa point.

Ice Sheet #8 One data point below 15 kPa, 14.9 kPa. The data point appears slightly high compared with the set as a whole.

Ice Sheet #9 Two data points below 15 kPa, 12.9 kPa and 14.5 kPa, which together with the remaining two data points, 20.2 kPa and 19.1 kPa form a consistent resistance curve with no apparent anomalies.

Ice Sheet #10 One data point below 15 kPa, 13.0 kPa, which shows a marked higher resistance (after correction) than the faster speed 22.8 kPa. Even before any correction, the resistance of the 13 kPa point is very similar to the higher speed, higher strength 22.8 kPa data point.

Ice Sheet #14 One data point, below 15 kPa, 13.4 kPa, showing no apparent anomalies.

The primary objective of this test program was to establish the relationship between the midbody length and resistance as a function of the two bow forms tested. In general, since the low strength data was limited to one or two data points in any one ice sheet it was thought that this objective could be accomplished with the data set available. Following the

data analysis, this assumption has been qualified to the extent that trends may be identified, but cannot be confirmed with confidence.

The second objective of the test program was to establish the relationship between the ice thickness and resistance for the Melville bow. A total of 12 data points were collected from three ice sheets (excluding the low speed tests) of which five points are associated with low strength values. The remaining data points are considered to be too few to confidently determine any ice thickness versus resistance trends and this second objective cannot be accomplished with any level of confidence with the data available in this program. As a result, the thickness versus resistance relationship, which is required for the length variation analysis, will be derived from data collected as part of other model test programs.

2.3.2 Data Correction

The model tests were all conducted with target ice thicknesses and strengths, however, as with any physical testing, the target values were not always obtained and there are standard correction procedures that may be used that permit comparisons between different ice sheets. However, as discussed above, it is considered that some of the data point variations were beyond those limits that can be corrected using these conventional procedures alone. As a result the data was corrected in two steps. The first step followed conventional methods and the second was applied only to those data points showing grossly inconsistent values after the initial correction. The conventional data correction technique adopted in this report has been discussed in a previous project undertaken by Melville in 1987 at the IMD tank (Melville 1987).

These standard correction procedures may be summarized as;

a) Ice thickness;

   The rate of change of resistance with thickness is calculated based on tests with the same model at the same speed in different ice thicknesses. This is then divided by the resistance of the model in the ice sheet with the closest thickness to the subject test. This yields a percentage change of resistance with thickness. The correction to the subject test is then calculated by multiplying the measured resistance by the difference between target and measured ice thickness and by the percentage rate of change of resistance with thickness.

b) Ice strength;

   Based on presawn, or zero strength, ice tests the percentage rate of change of resistance with ice strength is calculated. The correction to the subject test is then calculated by multiplying the measured resistance by the difference between target and measured ice strength and by the percentage rate of change of resistance with strength.

It is conventionally assumed that resistance data is normalized for thickness and strength separately, based on the measured resistance. The alternative is to apply corrections to the resistance values that include previous corrections. The result of this calculation will depend on which correction is applied first. This has been discussed in a previous report {Melville 1987} in which the results from two similar ice sheets were compared using the two methods. The result of this comparison indicated that data tended to give less consistent results when applied with multiple corrections, independently of which was applied first. As a result, all subsequent adjustments to the data in this report are calculated from adding the accumulated value of all the corrections to the measured resistance.

As discussed above, additional corrections were made to those data points associated with either low strength values or grossly inconsistent data points that were close to, and may have been influenced by, low strength areas of the ice sheet. These corrections were developed using an analysis of the available data and are discussed in detail in Appendix C.

However, for the purpose of completeness the data set is presented in Appendix F without the additional data corrections, but including the standard correction procedures.

Figures 2.3 to 2.8 present this data in graphical form as summarised below.

Figure 2.3: Figure 2.3 presents the results from the four different length variations that were tested with the Melville bow. It can be seen from these results that the 'existing' and 'no-midbody' results are fairly consistent but that both the other tests, the 'long ship' and particularly the 'half midbody' model give more erratic results. An overall trend does indicate that the resistance increases with length across the speed range, as may be expected, and that the 'long ship' demonstrates a stronger speed dependency than the remaining models.

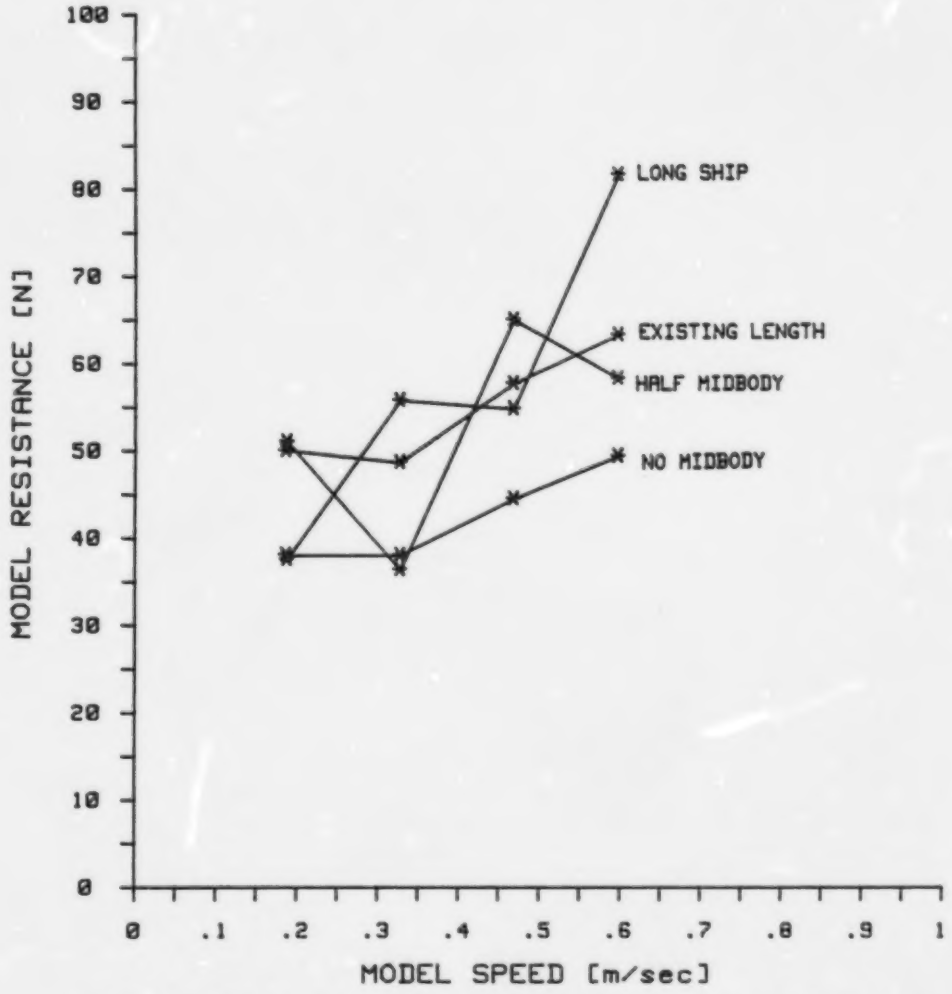
Figure 2.4: Figure 2.4 presents the results from the three different length variations with the Original bow. The scatter of data clearly makes any comparison of the data very difficult. The short ship does remain below the resistance of the existing ship length, however the long ship arguably has a lower resistance that both the short and existing ship lengths. A review of the ice data, together with observations of the model test do not suggest an explanation for these anomalies.

Figure 2.5: Figure 2.5 presents the range of friction coefficients tested for the Melville bow and short ship. The results are generally consistent and reflect predictable trends.

Figure 2.6: Figure 2.6 presents the results of the friction variation tested with the Original bow form. The results from the tests using friction coefficients of 0.33 and 0.004 appear to have a consistent trend. However, as with Figure 2.4, the 0.06 friction coefficient associated with the Original bow and

FIGURE 2.3

RESISTANCE vs SPEED FOR SERIES OF LENGTH VARIATIONS WITH THE MELVILLE BOW



Midbody test program ; Ice sheet #3 #7 #13 and #14
Data corrected to target strength and thickness
Target ice thickness = 0.03 m
Target ice strength = 19 kPa
Friction coefficient = 0.06

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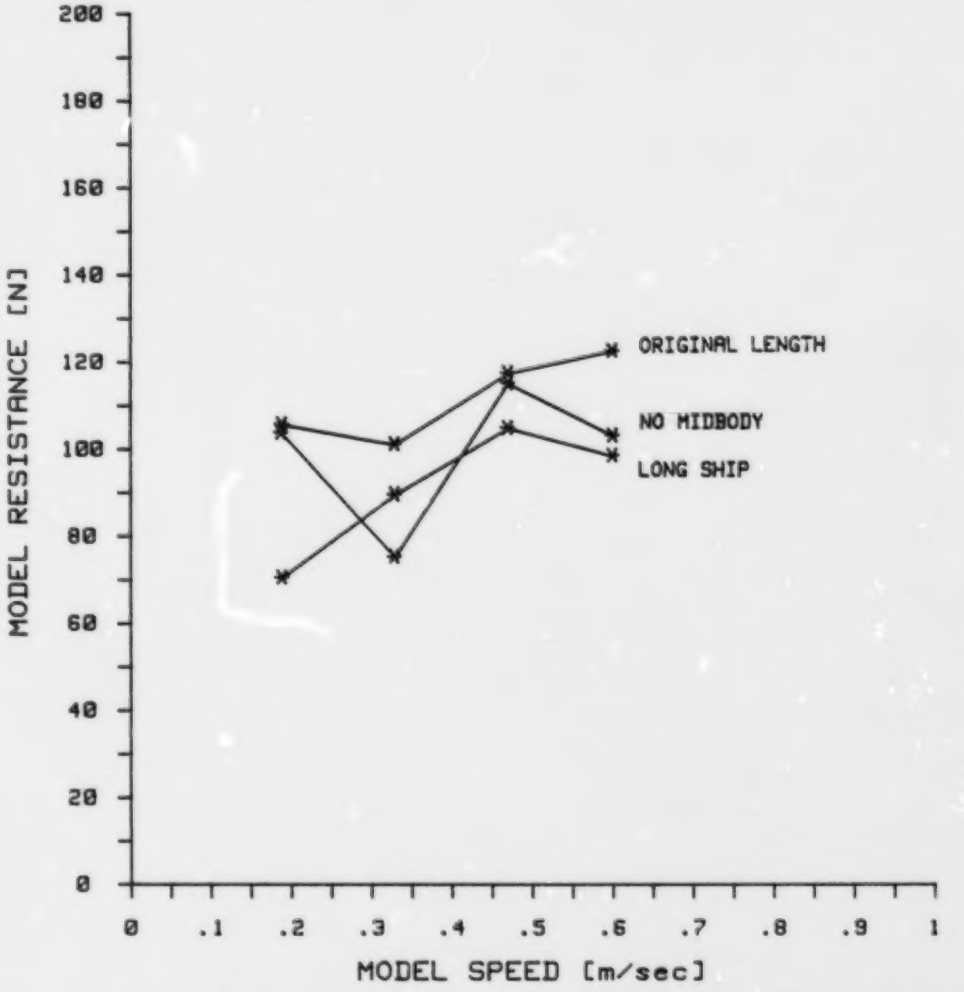
FIGURE 2.4

RESISTANCE vs SPEED FOR SERIES OF LENGTH VARIATIONS WITH THE ORIGINAL BOW



Midbody test program ; Ice sheet #10 #11 and #12
Data corrected to target strength and thickness
Target ice thickness = 0.03 m
Target ice strength = 19 kPa
Friction coefficient = 0.06

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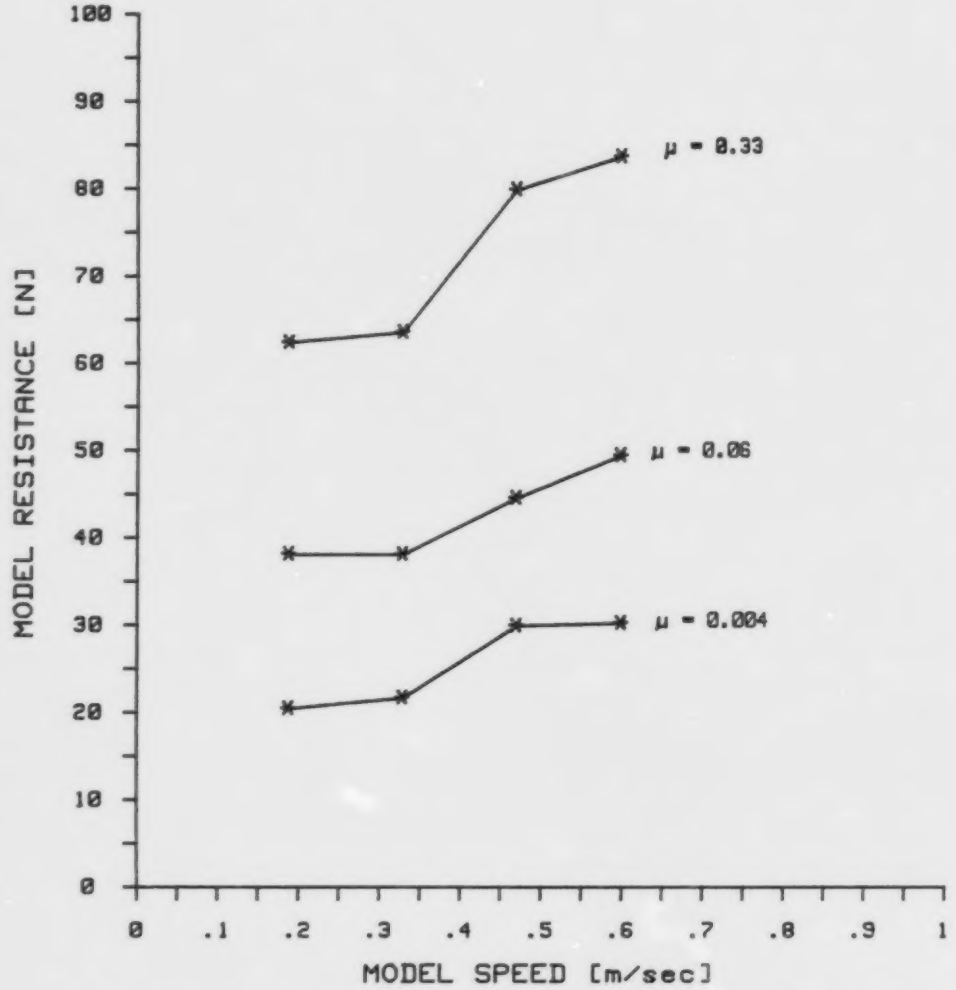
FIGURE 2.5

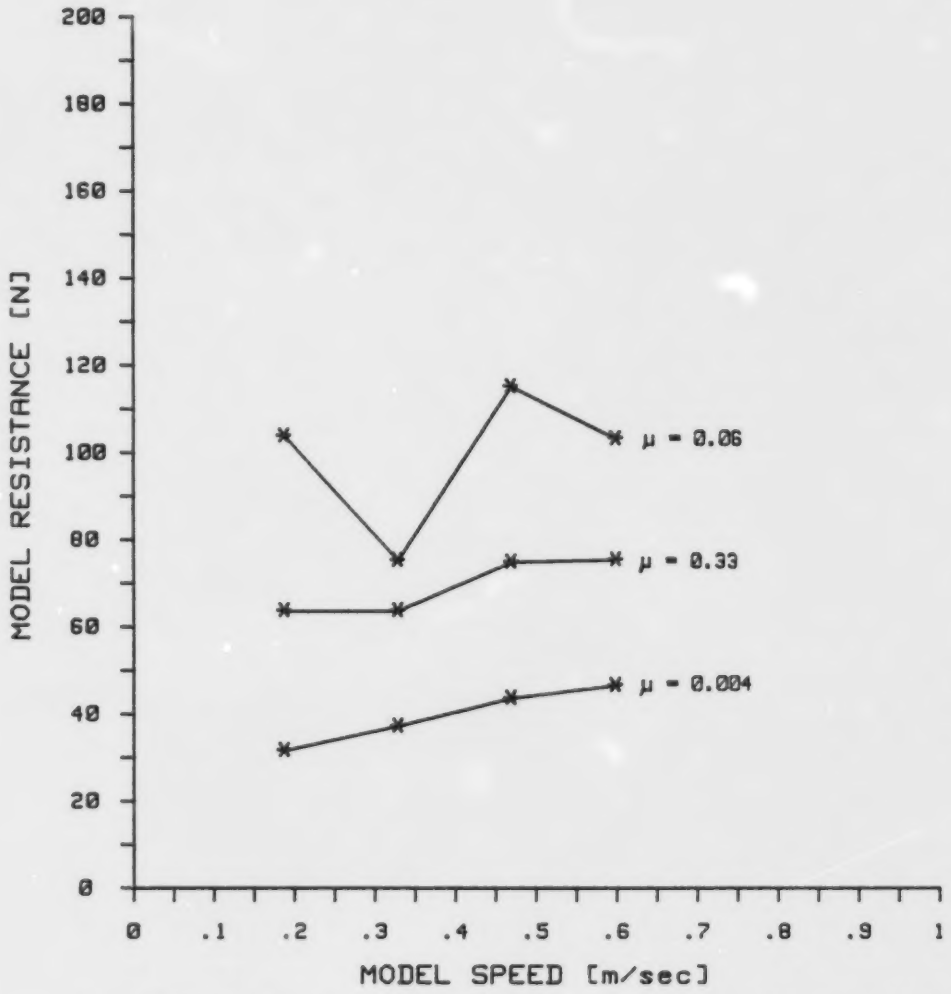
RESISTANCE vs SPEED FOR A SERIES OF FRICTION VARIATIONS WITH A SHORT SHIP AND THE MELVILLE BOW



Midbody test program ; Ice sheet #5 #7 and #8
Data corrected to target strength and thickness
Target ice thickness = 0.03 m
Target ice strength = 19 kPa
Friction Coefficient = 0.004 0.06 and 0.33

FIGURE 2.6

RESISTANCE vs SPEED FOR SERIES OF FRICTION VARIATIONS WITH A SHORT SHIP AND ORIGINAL BOW



Midbody test program ; Ice sheet #6 #9 and #10
Data corrected to target strength and thickness
Target ice thickness = 0.03 m
Target ice Strength = 19 kPa
Friction Coefficient = 0.004 0.06 and 0.33

existing ship length shows significant irregularity and results in a higher resistance than the model with the higher 0.33 friction coefficient.

Figure 2.7: Figure 2.7 presents the results from the tests for the Melville bow, with the ships existing length at two friction coefficients. The data is consistent and demonstrates a predictable relationship, although the speed dependency of the high friction surface is significantly stronger than for the lower friction surface.

Figure 2.8: Figure 2.8 illustrates the problems discussed earlier with the 40 mm ice sheet. These ice sheets are discussed in other parts of the report.

Although there is a strong suggestion from the data, briefly discussed above, that some of the erroneous data sets are caused by low ice sheet strengths, it should be noted that the majority of the problems were associated with the Original bow. This is a similar occurrence to the test program run in the HSVA ice tank in West Germany {Melville 1985}. During these tests similar, erratic, results were obtained and were considered to have been caused by ice floes breaking and rotating in such a manner that they became entrapped, on their edge, between the model and the unbroken ice sheet. This particular breaking pattern did not always occur and appeared to be associated with thicker ice.

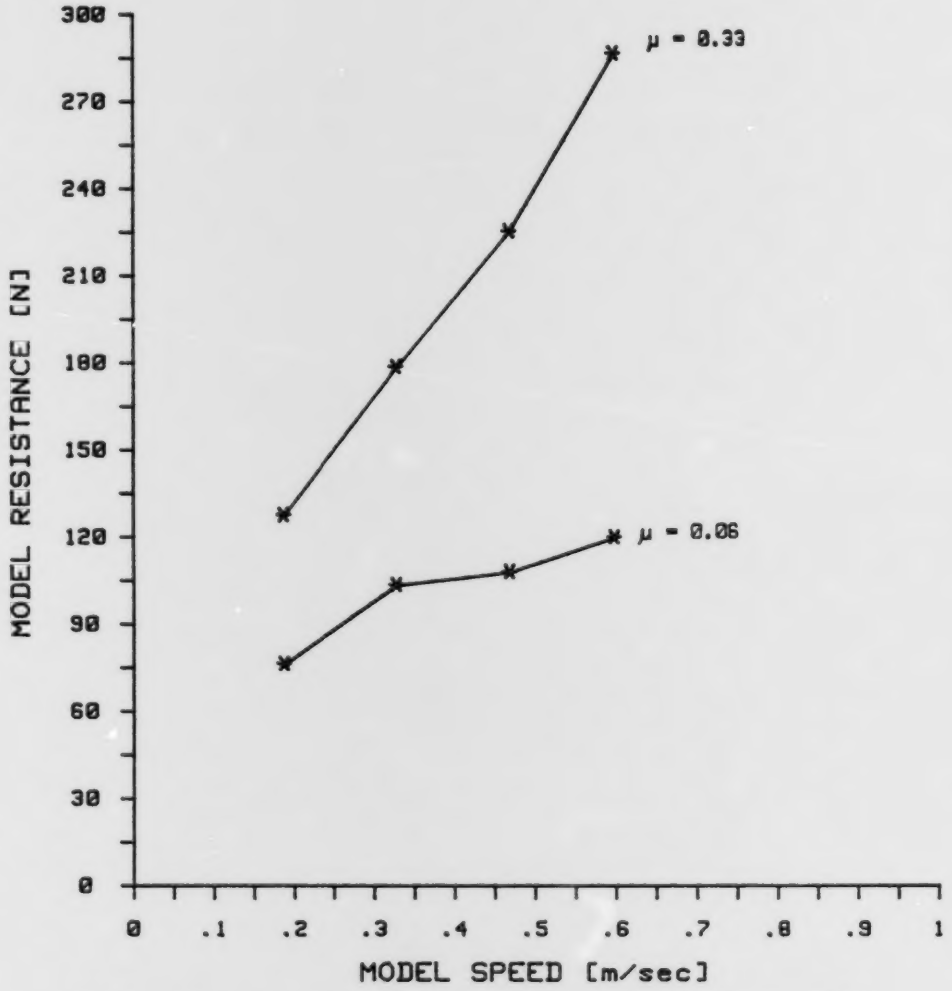
Unfortunately there is not sufficient data to determine whether this phenomenon is causing the erratic data but clearly suggests that the breaking pattern may significantly influence the resistance.

Appendix C presents the detailed analysis of the data set and how each ice sheet was reviewed and/or modified to permit a consistent set of relationships for subsequent analysis.

The remainder of this report presents the data after these corrections have been made unless specifically noted otherwise.

FIGURE 2.7

RESISTANCE vs SPEED FOR FRICTION VARIATION WITH EXISTING SHIP LENGTH AND MELVILLE BOW



Midbody test program ; Ice sheet #1 and #4
Data corrected to target strength and thickness
Target ice thickness = 0.05 m
Target ice Strength = 19 kPa
Friction Coefficient = 0.06 and 0.33

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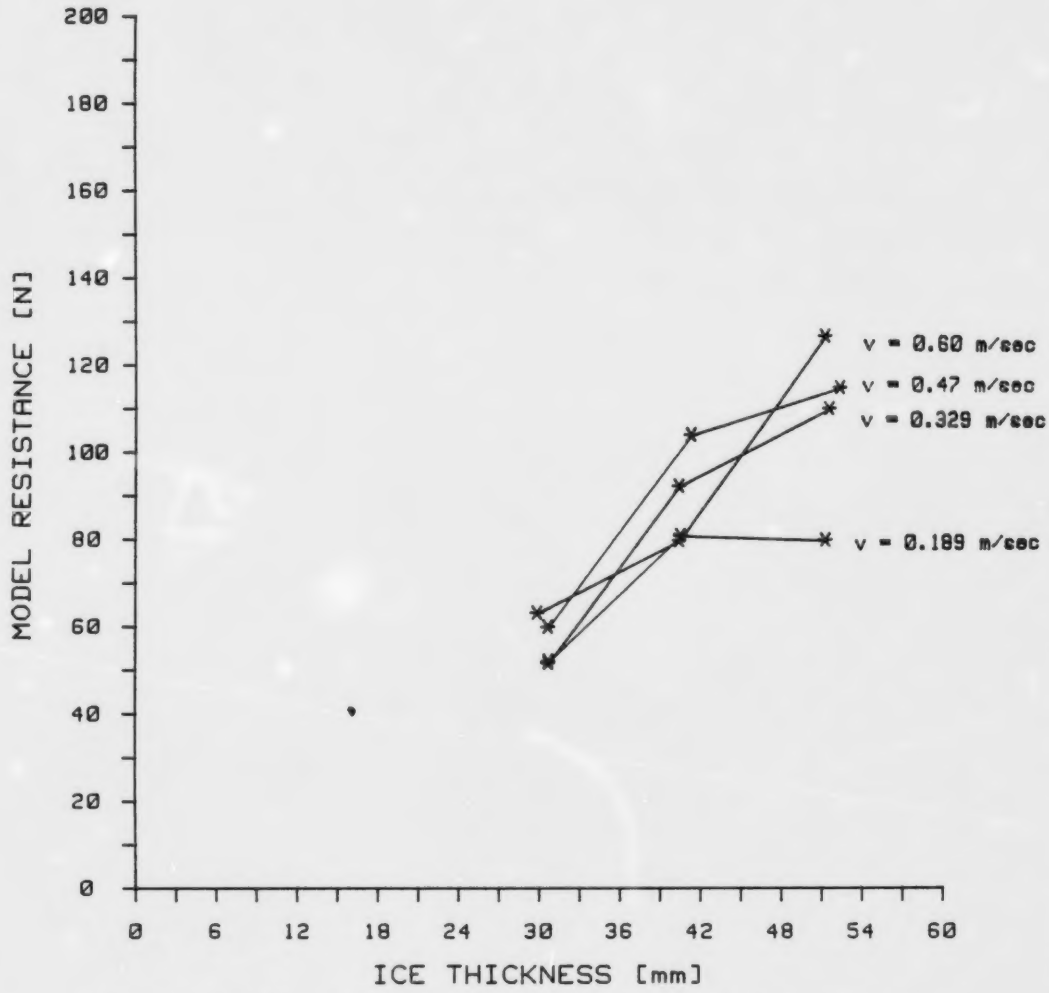
FIGURE 2.8

RESISTANCE vs THICKNESS FOR THE MELVILLE BOW OVER A RANGE OF SPEEDS



Midbody test program ; Ice sheet #1 #2 and #3
Data corrected to target strength and thickness
Target ice thickness = 0.03 0.04 and 0.05 m
Target ice Strength = 19 kPa
Friction Coefficient = 0.06

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3. ICE VARIABLE ANALYSIS

3.1 General

Part of the project objective is to develop relationships between resistance and the ice property variables that will permit adjustments to the model scale tests. These relationships were established from an analysis of the available model test data.

The model tests that have been reviewed were not all conducted at a common scale and, as a result, the following analysis has been completed using full scale values to permit some correlation between tests.

The analysis has been divided into two sections, a review of the thickness variation and a review of the strength variation. These are further subdivided into different test programs. The programs that have been found useful and used in the following analysis are;

Friction Program : An analysis of the friction coefficient on a 1:30 scale of the ARCTIC fitted with the Melville bow.
Full scale ice thickness = 1.2 to 1.5 m
Full scale ice strength = 570 kPa
Full scale ship; Length = 210 m
Beam = 23 m
{Melville 1987}

LOUIS Program : Alternative bow design testing on a 1:15 scale model of the CCG icebreaker LOUIS S. ST. LAURENT.
Full scale ice thickness = 0.7 to 1.5 m
Full scale ice strength = 450 kPa
Full scale ship; Length = 102 m
Beam = 24.4 m
{IMD 1987}

R-Class : Model tests with a 1:8 scale model of the R-Class CCG icebreaker.
Full scale ice thickness = 0.4 to 1.08 m
Full scale ice strength = 380 to 930 kPa
Full scale ship; Length = 86 m
Beam = 19.2 m
{Data obtained directly from IMD}

R-Class : Model tests with a 1:20 scale model of the R-Class CCG icebreaker.
Full scale ice thickness = 0.45 to 0.7 m
Full scale ice strength = 400 to 800 kPa
Full scale ship; Length = 86 m
Beam = 19.2 m
{ITTC 1987}

Simplified Hull Form : Model tests with a conceptual, simple, flat sided bow form.
Model scale ice thicknesses = 30 to 40 mm
Model scale ice strength = 30 to 70 kPa
{Data obtained directly from IMD}

Midbody Program : Model tests described in this report and consisting of tests with two different bow forms, four different length variations and four different friction coefficients.
Full scale ice thickness = 0.9 to 1.5 m
Full scale ice strength = 570 kPa
Full scale ship ; Length = 210 m Melville Bow
Length = 201 m Original Bow
Beam = 23 m

3.2 Thickness Variation

As the ice thickness increases it may be expected that the resistance will also increase by some value that may be dependent on a range of different factors. These may include the type of hull form, speed, ice strength and ice thickness. In order to analyse these influences each of the model test series described above have been corrected, using Froude scaling, to a constant value of 500 kPa using the presawn test analysis described in Section 2.

a) Friction Program

Figure 3.1 presents the variation of resistance as a function of thickness for the friction program. It can be seen from the curves that there does not appear to be a significant speed dependency on the resistance/thickness relationships which cover a speed range of 1 to 3.3 m/sec. The 2.57 m/sec test has the highest rate of change of resistance with thickness of 2.9 MN/m and the 1.81 m/sec test has lowest of 1.98 MN/m. The average is 2.33 MN/m.

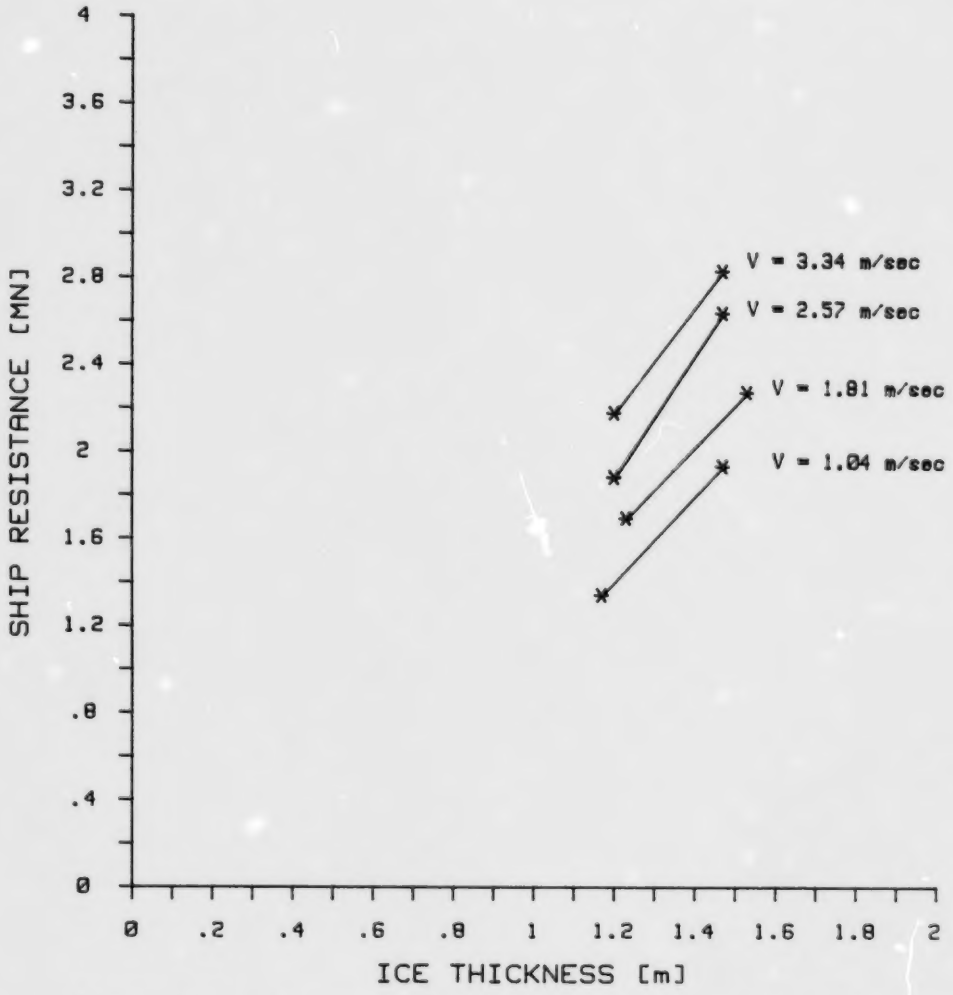
b) LOUIS Program

Figure 3.2 presents the variation of resistance as a function of thickness for the LOUIS program. The figure presents two different bow forms which were tested as part of the LOUIS program; the Melville bow and the ship's Original bow. It can be seen from the figure that the thickness dependency for each bow tends to increase with speed and that a difference exists between the two bow form configurations.

The rate of change of resistance with thickness for the Original bow varies from a maximum of 3.98 MN/m for the 3.0 m/sec point to a minimum of 2.55 MN/m at 1.0 m/sec with an average of 3.14 MN/m. In comparison, the Melville bow rate of change of resistance varies from 3.11 MN/m at 3.0 m/sec to 2.07 MN/m at 1.0 m/sec with an average of 2.53 MN/m. In addition to the Original and Melville type of bow form, an R-Class type bow was also tested in

FIGURE 3.1

RESISTANCE vs THICKNESS FOR THE MELVILLE BOW OVER A RANGE OF SPEEDS

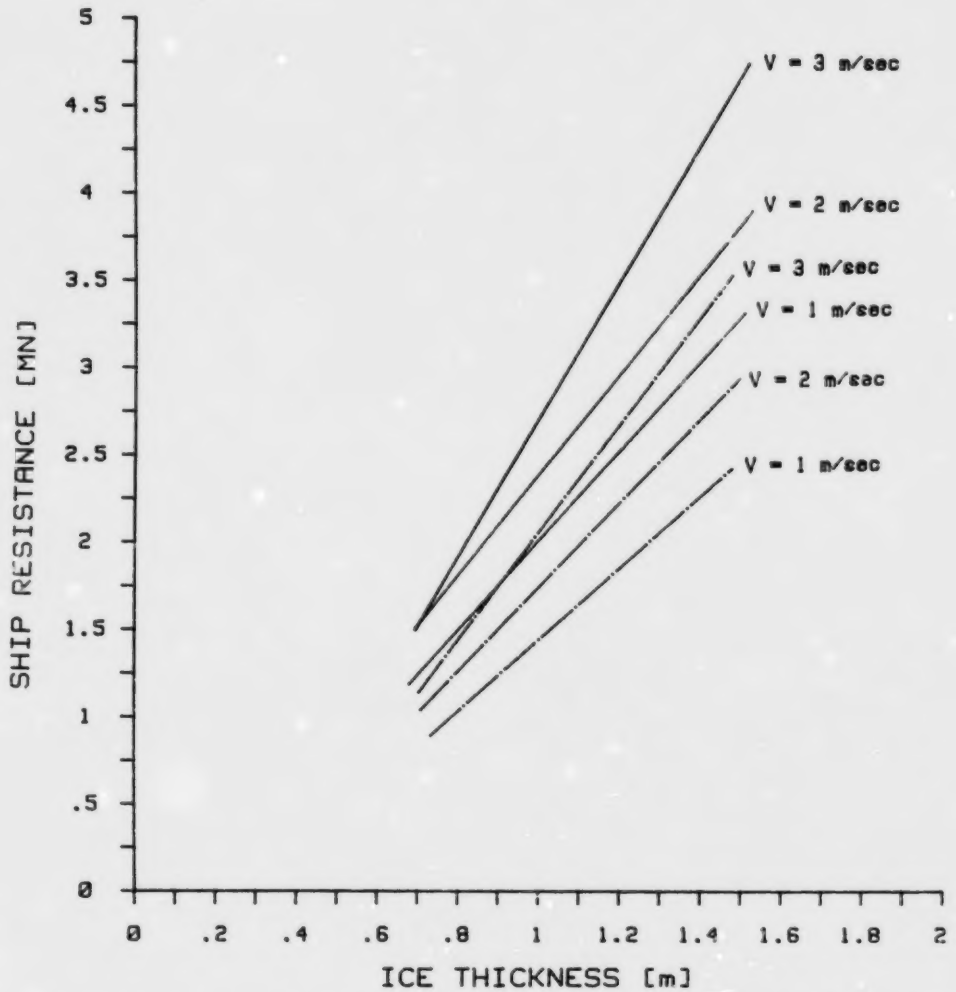


Friction test program ; Ice sheet #1 and #2
Data corrected to target strength only
Target ice thickness = 1.2 and 1.5 m
Target ice strength = 500 kPa
Friction Coefficient = 0.06

FIGURE 3.2

RESISTANCE vs THICKNESS FROM THE LOUIS TEST PROGRAM FOR TWO BOW FORMS OVER A RANGE OF SPEEDS

(ORIGINAL vs MELVILLE BOW)



Louis test program ; Ice sheet #1 #2 #3 #8 #9 and #1.
Data corrected to target strength only
Target ice thickness = 0.7 1.0 and 1.5 m
Target ice strength = 500 kPa
Friction Coefficient = 0.1
Original Louis Bow = Solid line
Melville Bow = Broken line

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the program. Figure 3.3 illustrates the comparison between the Original and R-Class forms. As with the first comparison there is some difference between the bow forms. The R-Class rate of change of resistance with thickness ranges from a maximum of 3.77 MN/m at 3 m/sec to 2.41 MN/m at 1 m/sec. The average value is 3.01 MN/m.

It is interesting to note that two quite different bow forms, the Original LOUIS and R-Class, have similar average values of rate of change of resistance (3.14 and 3.01 MN/m, respectively) with thickness, whilst the Melville bow has a significantly lower value (2.53 MN/m).

c) R-Class 1:8

This test series was conducted at a very small scale ratio that resulted in possibly the largest model that will ever be tested in an ice tank. Figure 3.4 presents the resistance versus ice thickness relationship over a range of speeds from 0.68 m/sec to 2.69 m/sec. The rate of change of resistance with thickness varies from 0.94 MN/m at the low speed to 1.14 MN/m at 2.69 m/sec.

d) R-Class 1:20

The 1:20 R-Class data is taken from the International Towing Tank Committee (ITTC) report on ice testing. The testing included an extensive series of model tests from a number of ice tanks around the world, including the IMD tank. For the purposes of this report only the IMD tank results are reviewed. Figure 3.5 presents the resistance versus thickness relationship for this test series. As with the test series discussed above the rate of change of resistance with thickness tends to increase with speed. The slope of the lines shown in Figure 3.5 range from 0.84 MN/m at 0.47 m/sec to 2.11 MN/m at 5.59 m/sec. It is unfortunate that the range of ice thicknesses tested is not very large and only ranges from about 25 mm to 35 mm model scale or 0.5 m to 0.7 m full scale.

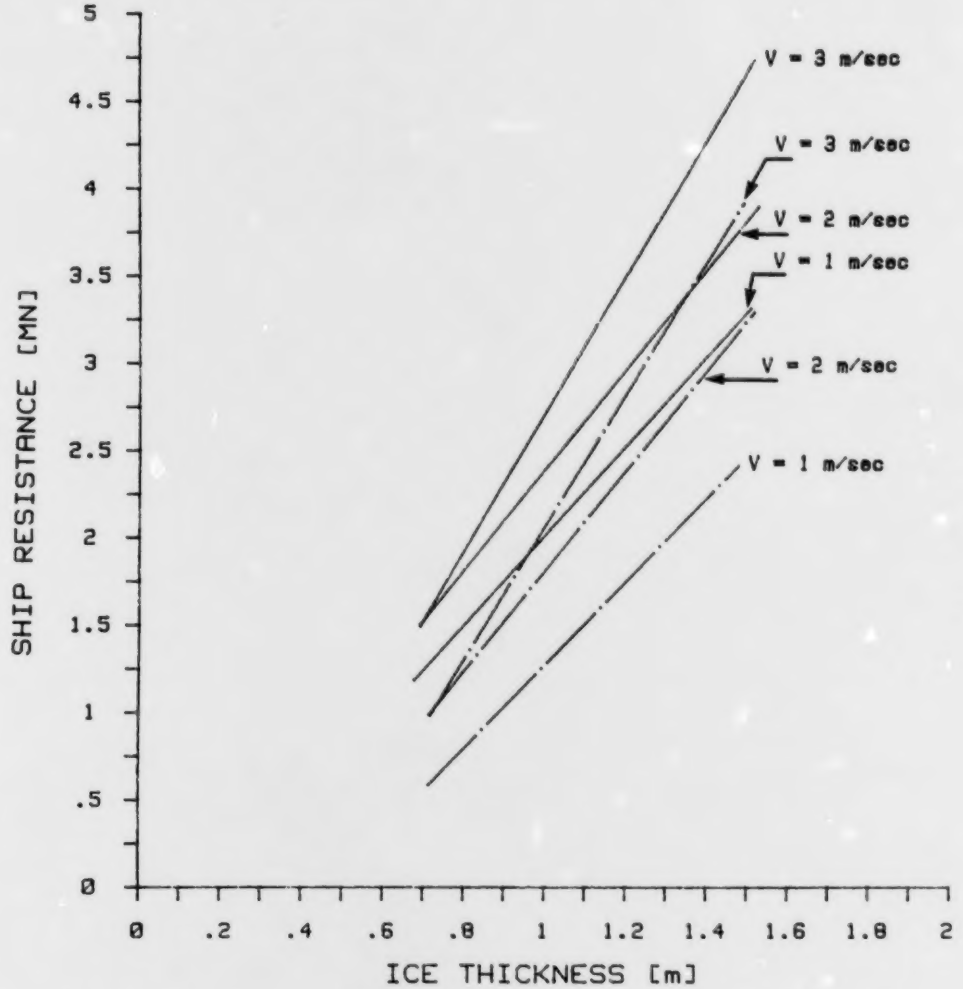
e) Simplified Hull Form

The simplified hull form tests were not designed to be conducted at any particular scale since they represent an idealistic form. However, to permit some correlation with the other bow forms it was elected to assign a scale of 1:23. This resulted in a full scale beam, the same as the ARCTIC (22.93 m) and similar to both the LOUIS, (24.4 m) and the R-Class, (19.2 m). The resultant rate of change of resistance with thickness is presented on Figure 3.6. The values range from 2.68 MN/m at the highest speed of 4.8 m/sec to 1.52 MN/m at 0.48 m/sec. As with the other test programs there is a general trend for the rate of change of resistance with thickness to increase with speed.

FIGURE 3.3

RESISTANCE vs THICKNESS FROM THE LOUIS TEST PROGRAM FOR TWO BOW FORMS OVER A RANGE OF SPEEDS

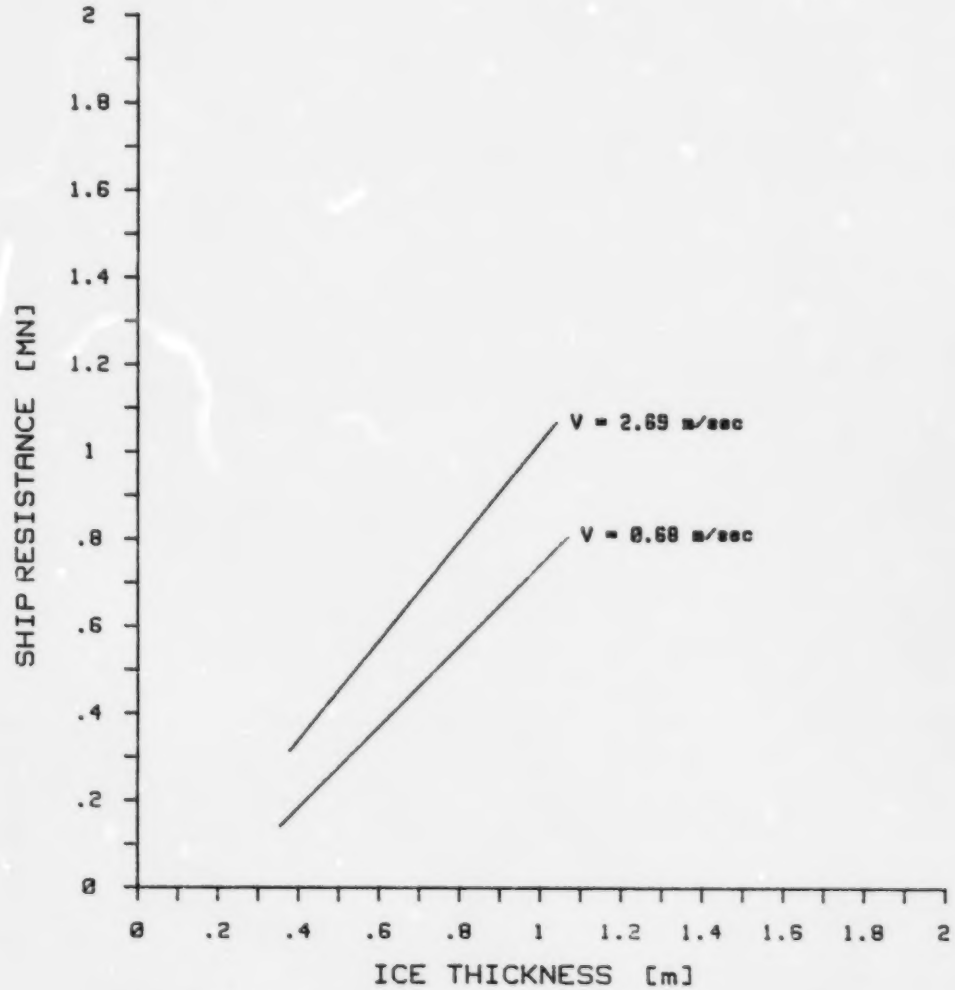
(ORIGINAL vs R-CLASS BOW)



Louis test program ; Ice sheet #1 - 3 and #4 - 7
Data corrected to target strength only
Target ice thickness = 0.7 1.0 and 1.5 m
Target ice strength = 500 kPa
Friction Coefficient = 0.1
Original Louis Bow = Solid line
R-Class Bow = Broken line

FIGURE 3.4

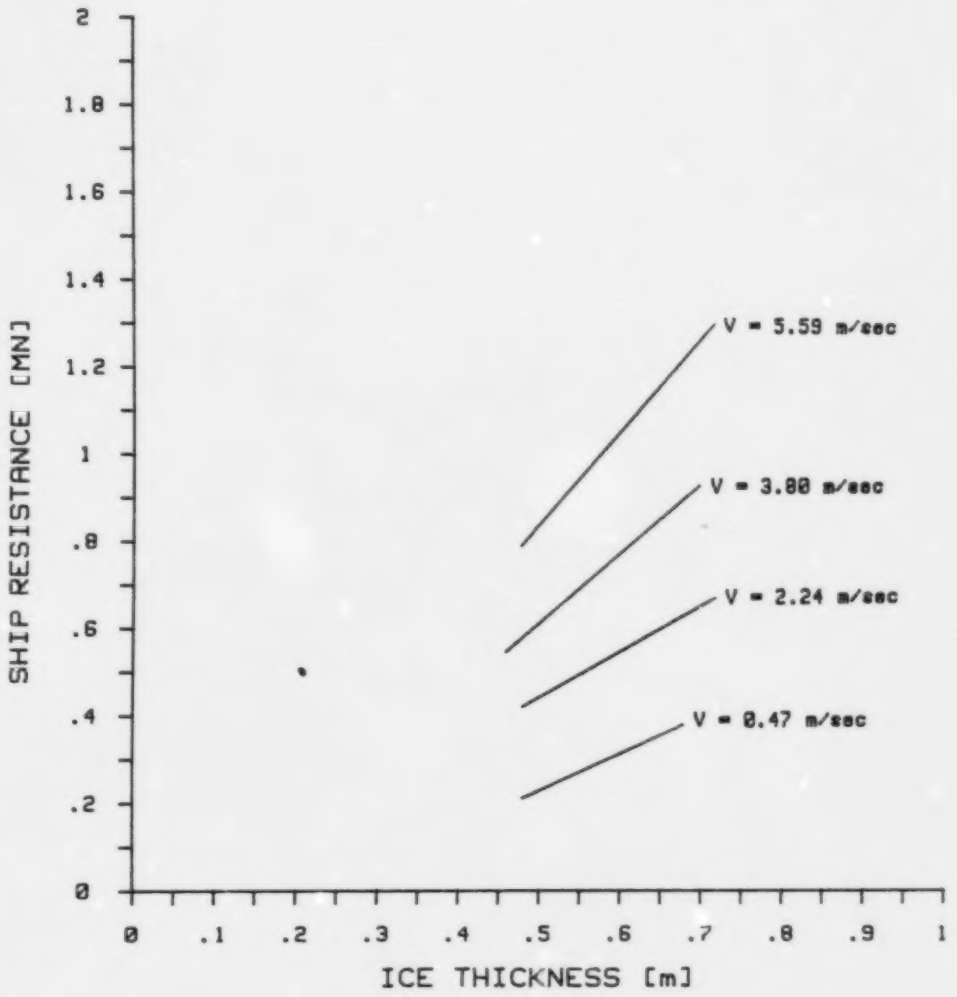
RESISTANCE vs THICKNESS FROM THE 1:8 R-CLASS TEST PROGRAM OVER A RANGE OF SPEEDS



1:8 R-Class program ; Ice sheets #1 - 10
Data corrected for strength
Target ice thickness = 0.4 to 1.1 m
Target ice strength = 500 kPa

FIGURE 3.5

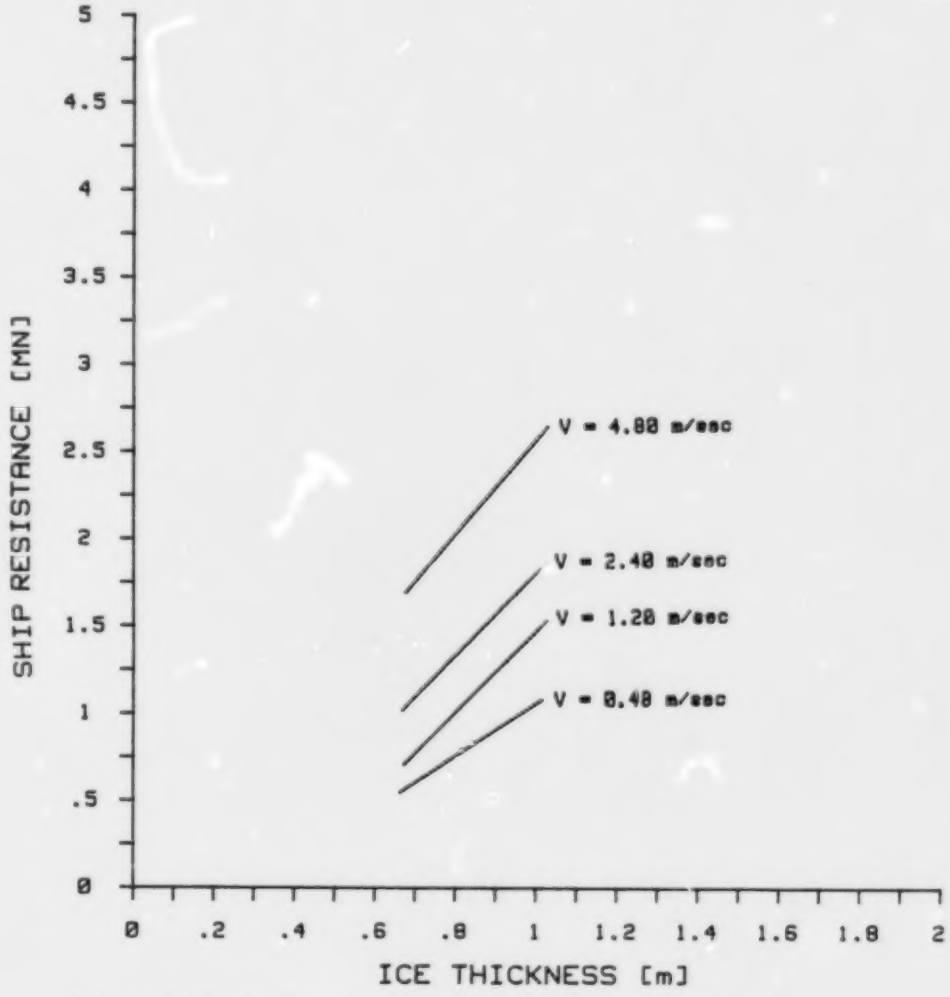
RESISTANCE vs THICKNESS FROM THE ITTC R-CLASS TEST PROGRAM CONDUCTED AT IMD



ITTC R-Class program ; IMD test series
Data corrected for strength
Target ice thickness = 0.5 and 0.7 m
Target ice strength = 500 kPa
Friction coefficient = 0.1

FIGURE 3.6

RESISTANCE vs THICKNESS FROM THE IMD SIMPLIFIED HULL FORM PROGRAM



Simplified hull form scaled by 1:23
Data corrected for strength
Target ice thickness = 0.6 to 1.0 m
Target ice strength = 500 kPa

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f) Midbody Length Program

Although the primary objective of the midbody program was to investigate the influence of midbody length on resistance, a series of three thickness variation tests were conducted on the ARCTIC fitted with the Melville bow. The results of these tests are shown in Figure 3.7. It should be noted that the 40 mm ice sheet contained questionable data points due to low strength properties of the ice. These have been adjusted as described in Appendix C. Figure 3.7 presents the data after this correction. The rate of change of resistance with thickness ranged from 1.55 MN/m at 1.03 m/sec to 2.42 MN/m at 3.29 m/sec. As with the other test programs, the rate of change of resistance with thickness tended to increase with speed.

A comparison of the above analysis is summarized in Table 3.1 and Figure 3.8. The table presents the full scale rate of change of resistance with thickness for each model configuration at three speeds, obtained from a linear interpolation between the model test speeds.

It can be seen from the figure that the rate of change of resistance with thickness is a function of bow type. It should also be noted that Figure 3.8 is based on an average thickness.

In an attempt to recognize a range of thicknesses in the correction procedure the rate of change of resistance with thickness has been non-dimensionalized using resistance and thickness. The result is a non-dimensional correction factor for thickness that is the rate of change of resistance with thickness, multiplied by the ratio of thickness and resistance. This product has been called the "thickness correction factor".

These calculated values are presented in Table 3.1 and Figure 3.9. There are two observations that may be made;

- There does not appear to be a consistent speed dependency for any one type of bow, and

- There is little correlation between similar bows or model scales.

Unfortunately there is insufficient data to develop this relationship further, however in an attempt to address this problem further, a sensitivity analysis was conducted on the non-dimensional correction factor. The following test series were used for the analysis;

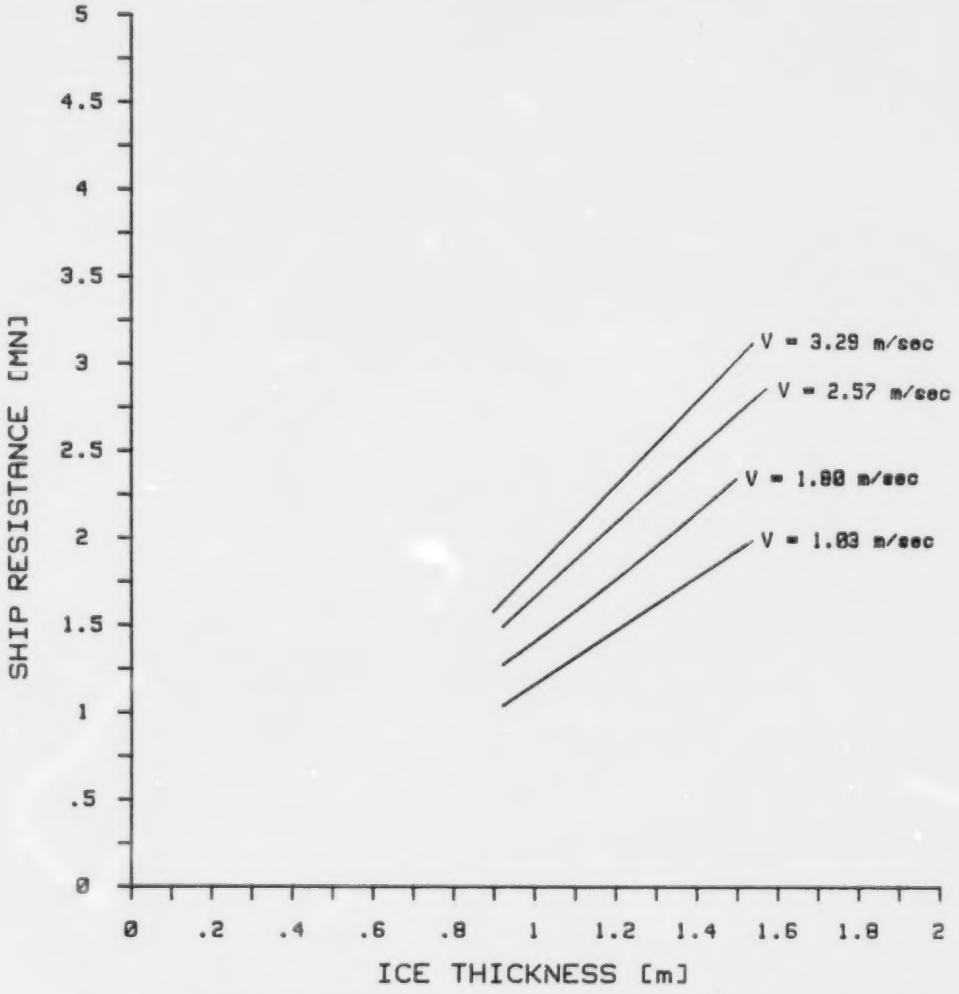
a) Midbody Program

The first three ice sheets in the midbody test program were 30 mm, 40 mm and 50 mm thick. The data was adjusted to full scale using Froude scaling laws and then corrected to a strength of 500 kPa,

FIGURE 3.7

RESISTANCE vs THICKNESS FROM THE MIDBODY LENGTH VARIATION PROGRAM

(MELVILLE BOW)



Midbody test program ; Ice sheets #1 #2 and #3
Data corrected for strength
Target ice thickness = 0.9 1.2 and 1.5 m
Target ice strength = 500 kPa
Friction coefficient = 0.06

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TABLE 3.1

RATE OF CHANGE OF RESISTANCE WITH ICE THICKNESS

HULL FORM	MODEL SCALE	LENGTH [m]	B [m]	SPEED m/sec	RATE OF CHANGE OF RESISTANCE MN/m	THICKNESS CORRECTION FACTOR
Friction Program;						
Melville Bow on						
the ARCTIC	30	206.0	23.00	1	2.02	1.61
				2	2.04	1.37
				3	2.35	1.28
Louis Program;						
Melville Bow on						
LOUIS S ST LAURENT	15	102.0	24.40	1	2.07	1.44
				2	2.42	1.36
				3	3.11	1.38
R-Class Bow on						
LOUIS S ST LAURENT	15	106.7	24.40	1	2.41	1.42
				2	2.86	1.52
				3	3.77	1.73
Original Bow on						
LOUIS S ST LAURENT	15	106.7	24.40	1	2.55	1.42
				2	2.89	1.20
				3	3.98	1.24
1:8 R-Class Program	8	98.3	19.43	1	0.97	1.42
				2	1.07	1.28
				3	1.17	1.15
ITT, R-Class Program	20	98.3	19.43	1	0.90	1.69
				2	1.00	1.22
				3	1.28	0.95
Simplified Hull						
Form	23	103.5	23.00	1	2.01	1.64
				2	2.18	1.47
				3	2.36	1.33
Midbody Program;						
Melville Bow on						
the ARCTIC	30	206.0	23.00	1	1.54	1.27
				2	1.90	1.25
				3	2.30	1.24

FIGURE 3.8

RATE OF CHANGE OF RESISTANCE WITH THICKNESS
VERSUS SPEED

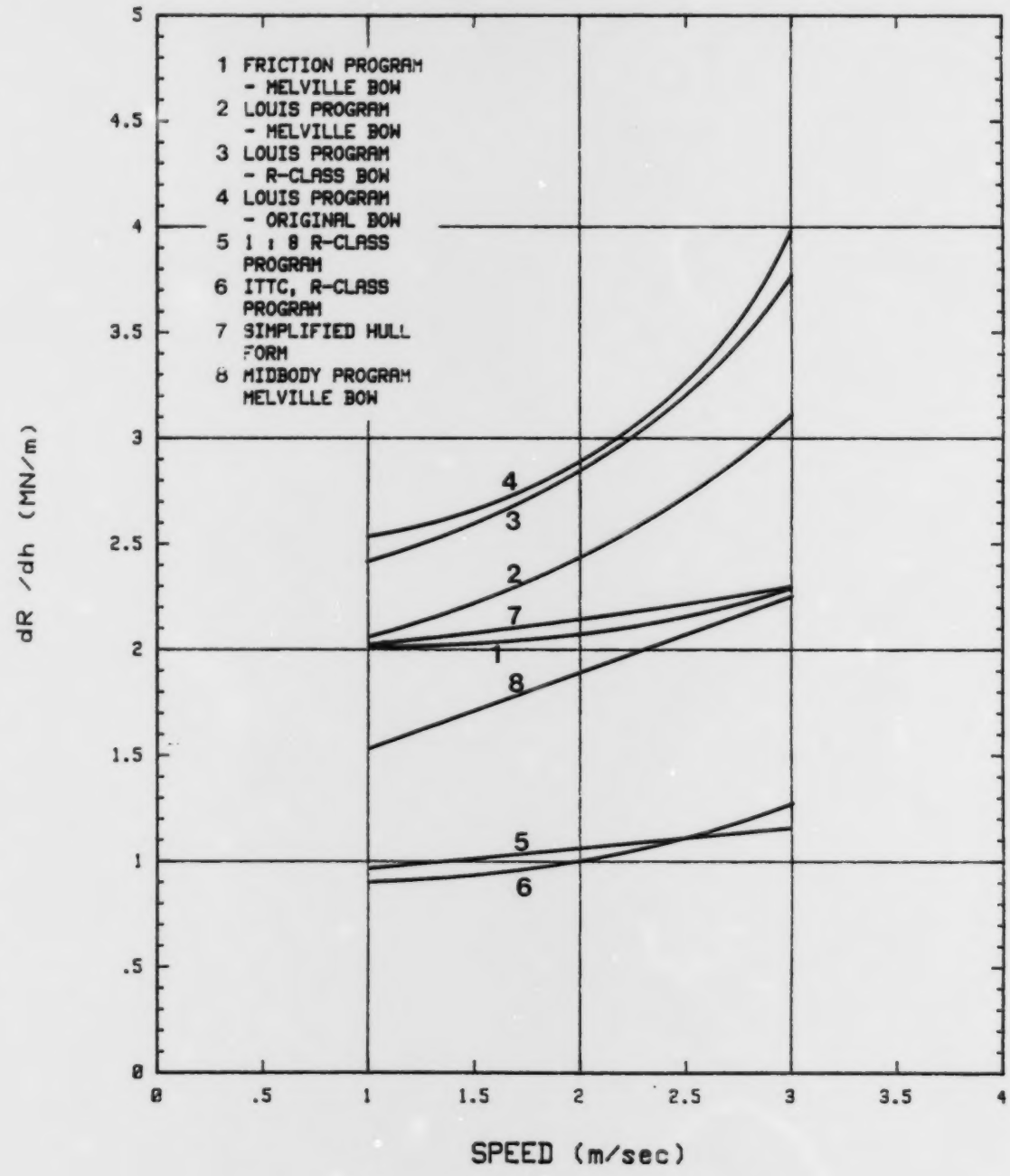

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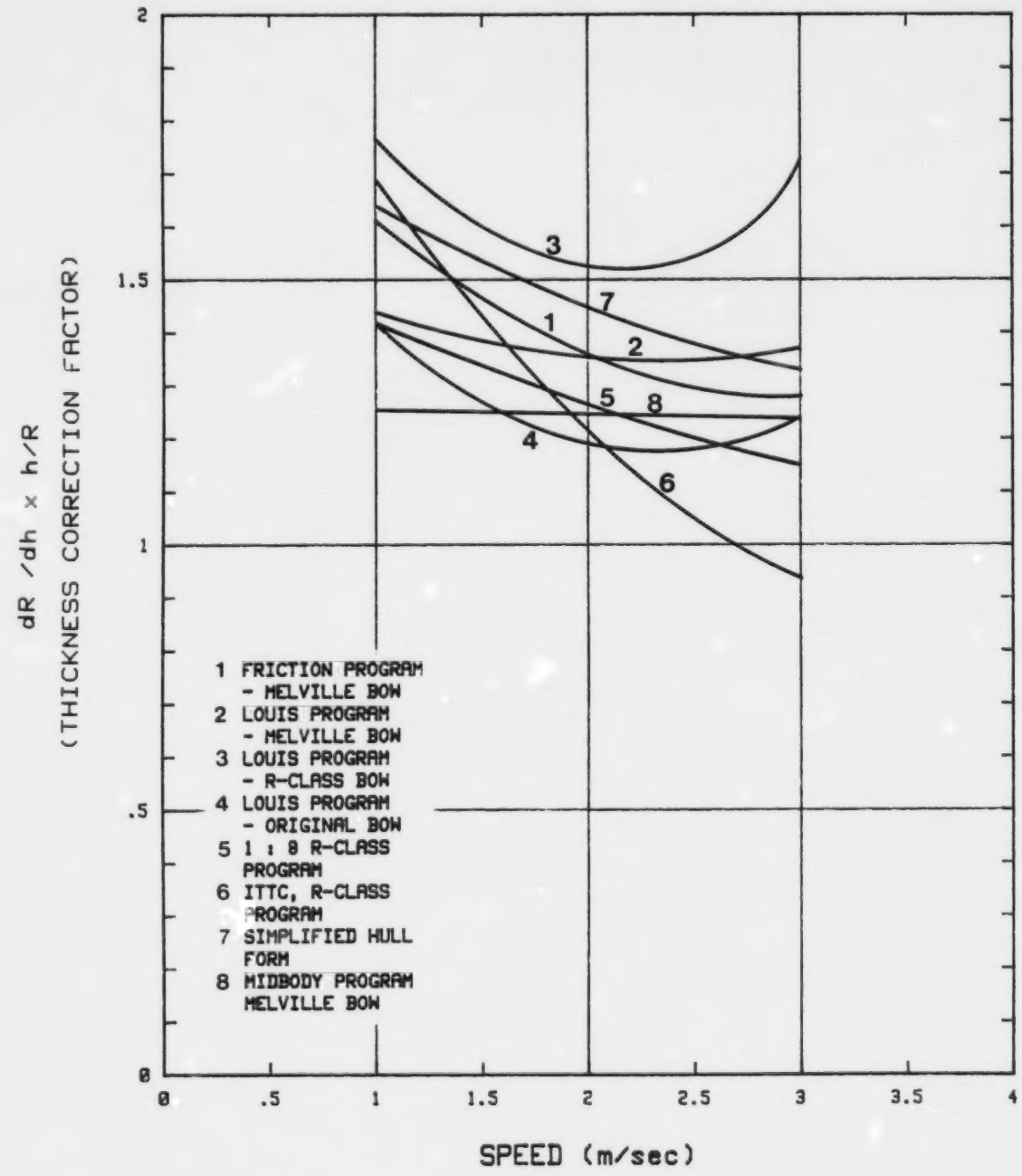
FIGURE 3.9

NON DIMENSIONAL RATE OF CHANGE OF
RESISTANCE WITH THICKNESS VERSUS SPEED



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using the presawn ice sheet data. To investigate the sensitivity to resistance, a range of non-dimensional correction factors were used to correct the three sheets to a single target thickness of 1.2 m. Figures 3.10 to Figure 3.12 present the test data corrected to 1.2 m using thickness correction factors of 1.0, 1.5 and 1.25 respectively. The target value, based on Figure 3.9 for the Melville bow, in the midbody program is about 1.25 and, as can be seen from Figure 3.12, this value gives the closest correlation. The effect of using a thickness correction factor of 1.0 results in an 11 percent spread of data at 2 m/sec and using 1.5 results in a 13 percent spread at 2 m/sec.

b) LOUIS Program

The LOUIS program consisted of three bow form types. Each was corrected for strength using presawn ice sheet data and then corrected for thickness, using the non-dimensional correction factor developed above. Figure 3.13 presents the data for a thickness correction factor of 1.2 based on the results given in Figure 3.9. It can be seen from the figure that the 1.2 correction factor correlates well for the 1.5 m and 1.2 m test data but does not for the 0.9 m test data. One possible explanation for this may be seen by reviewing the data from the LOUIS test program. Figure 3.14 presents the results from this program for the Melville bow in the form of resistance versus thickness. It can be seen from this figure that the rate of change of resistance with ice thickness increases in thinner ice. Comparing this result to the similar resistance versus thickness relationship for the midbody program, presented in Figure 2.8, demonstrates a different relationship with the midbody data showing a constant rate of change of resistance with ice thickness. Whether this is a characteristic of the model scale or the particular form of the Melville bow used for the LOUIS tests is not known.

c) Friction Program

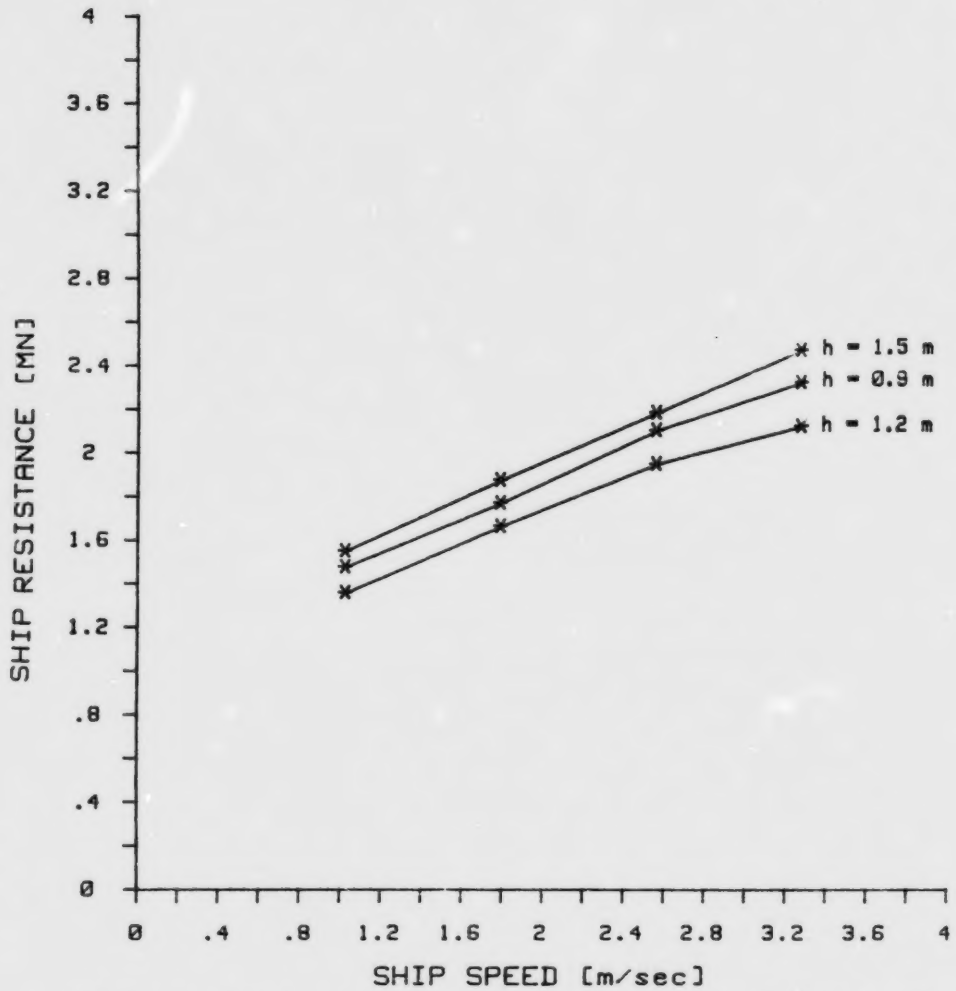
Two ice thicknesses were tested in the friction program representing 1.2 and 1.5 m full scale with the existing ship configuration. From Figure 3.9 the thickness correction factor for these tests should be about 1.4. Figure 3.15 presents the results of using this correction factor on the data. The effect of using 1.25, based on the midbody program of results, is shown in Figure 3.16. Clearly the different correction factors result in very minor differences in resistance.

The above analysis demonstrates that, if ice thicknesses are to be adjusted, a reasonable level of accuracy may be obtained by using the scaling factor defined by the non-dimensionalized rate of change of resistance with thickness. The results indicate that there is some variation in this factor as a function of bow shape but, for practical purposes, results in consistent data adjustment. This procedure is used in Section 4 to analyse the effect of varying displacement and ship parameters.

FIGURE 3.10

RESISTANCE VERSUS SPEED FOR A RANGE OF ICE THICKNESS DATA CORRECTED TO 1.2 m

(MELVILLE BOW)



Midbody test program ; Ice sheets #1 #2 and #3
Data corrected for thickness and strength
Target ice thickness = 1.2 m
Target ice strength = 500 kPa
Friction coefficient = 0.06
Thickness correction factor = 1.0

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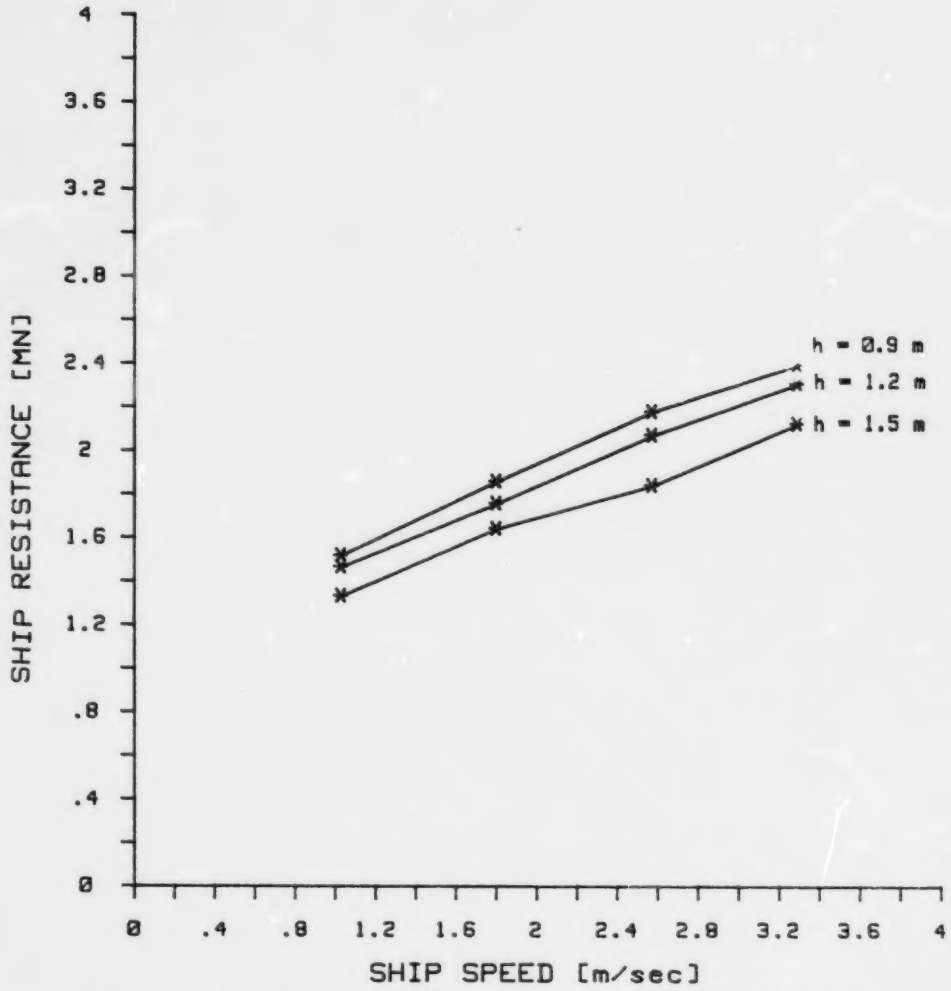
FIGURE 3.11

RESISTANCE VERSUS SPEED FOR A RANGE OF ICE THICKNESS DATA
CORRECTED TO 1.2 m

(MELVILLE BOW)



Midbody test program ; Ice sheets #1 #2 and #3
Data corrected for thickness and strength
Target ice thickness = 1.2 m
Target ice strength = 500 kPa
Friction coefficient = 0.06
Thickness correction factor = 1.5

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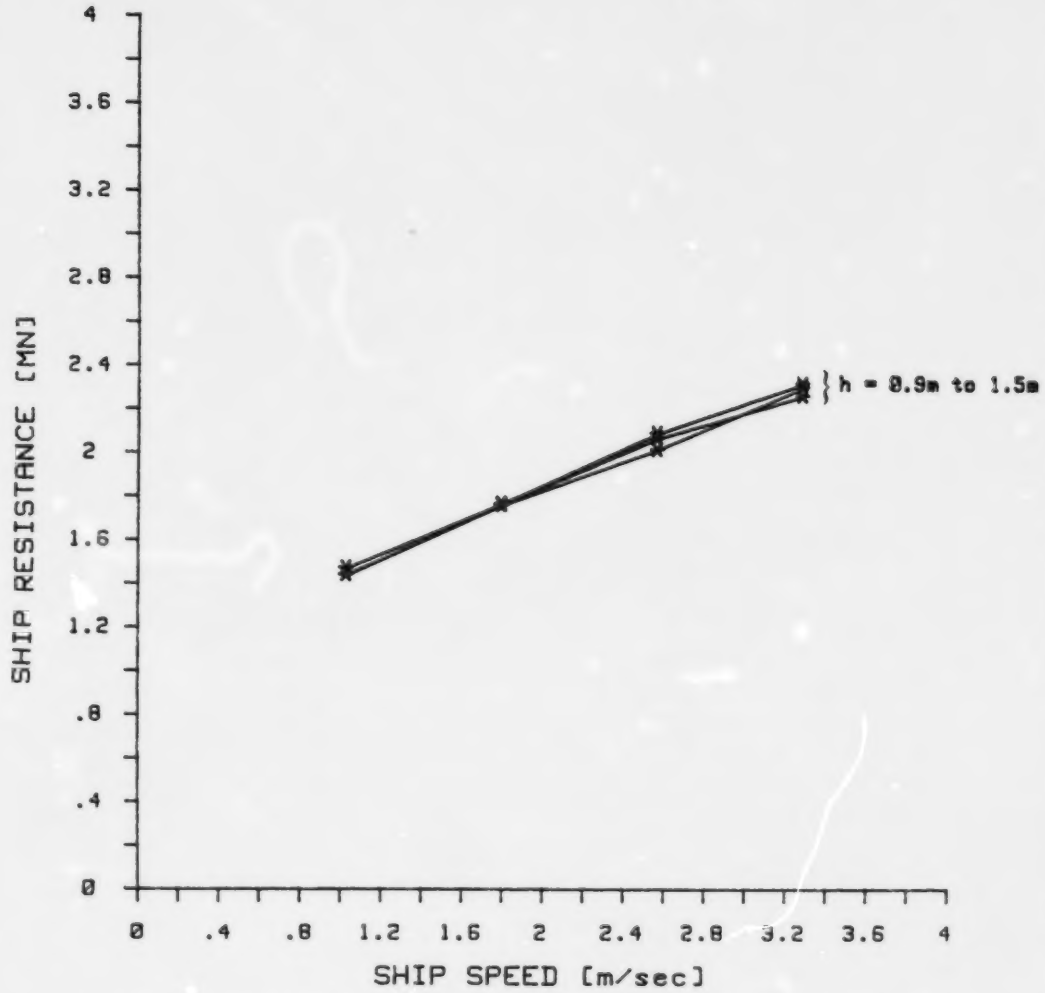
FIGURE 3.12

RESISTANCE VERSUS SPEED FOR A RANGE OF ICE THICKNESS DATA CORRECTED TO 1.2 m

(MELVILLE BOW)



Midbody test program ; Ice sheets #1 #2 and #3
Data corrected for thickness and strength
Target ice thickness = 1.2 m
Target ice strength = 500 kPa
Friction coefficient = 0.06
Thickness correction factor = 1.25

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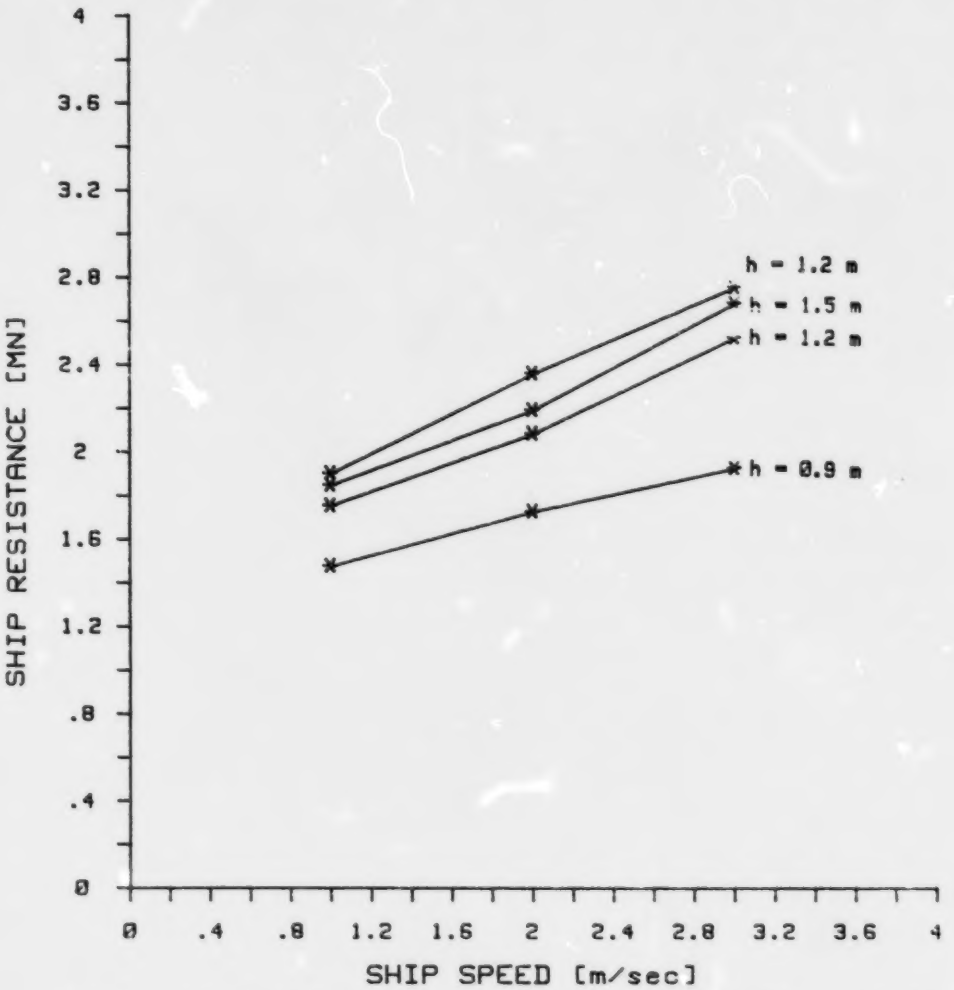
FIGURE 3.13

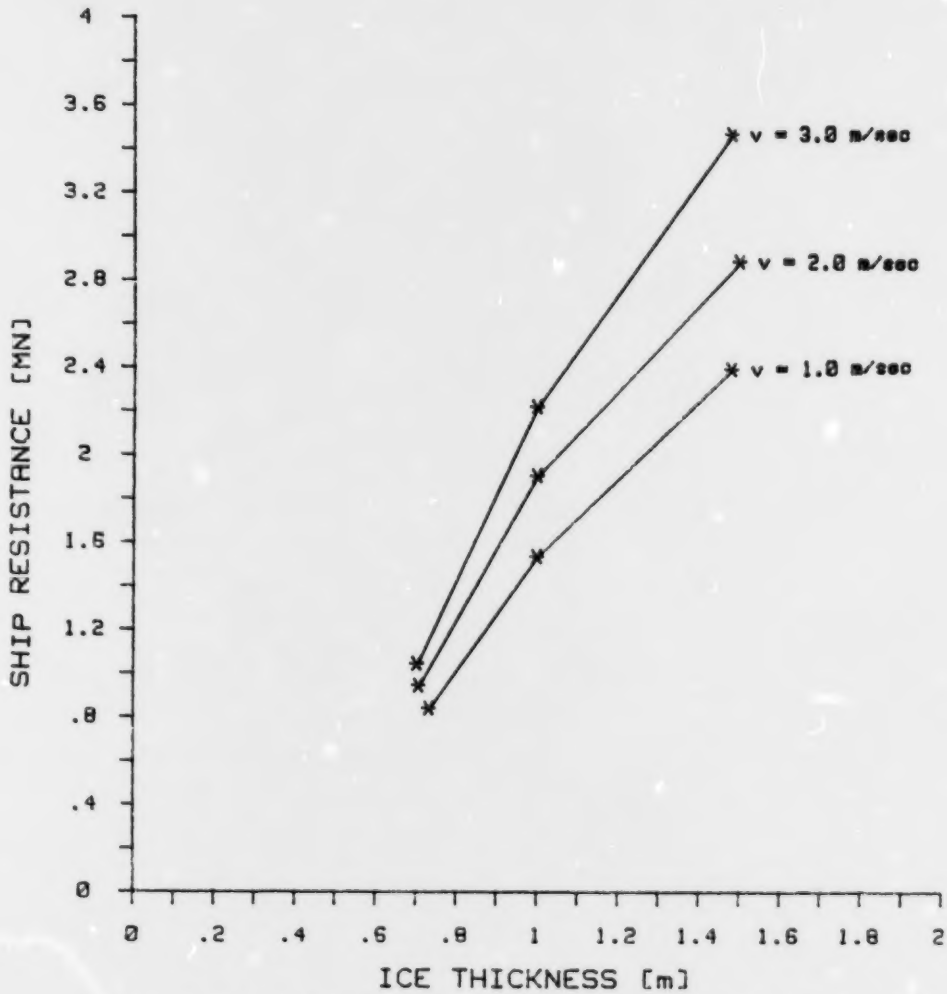
FULL SCALE RESISTANCE vs SPEED FOR A RANGE OF THICKNESS CORRECTED TO 1.2 m



Louis test program ; Ice sheet #8 #9 #10 and #11
. ; Melville bow
Data corrected for thickness and strength
Target ice thickness = 1.2 m
Target ice strength = 500 kPa
Friction coefficient = 0.1
Thickness correction factor = 1.2

FIGURE 3.14

FULL SCALE RESISTANCE vs THICKNESS FROM THE LOUIS TEST PROGRAM USING THE MELVILLE BOW



Louis test program ; Ice sheets #9 #10 and #12
Data corrected for strength
Target ice thickness = 0.9 1.0 and 1.5 m
Target ice strength = 500 kPa
Friction coefficient = 0.1

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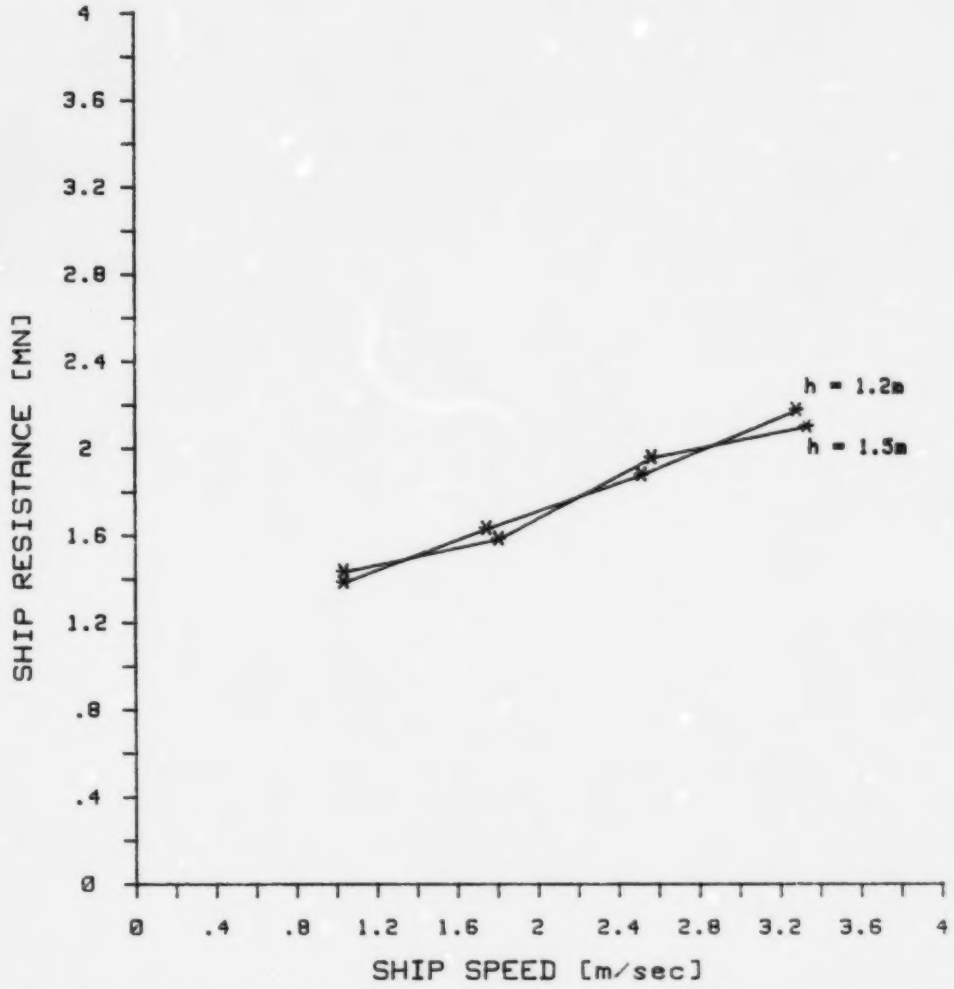
FIGURE 3.15

FULL SCALE RESISTANCE vs SPEED FOR A RANGE OF THICKNESS CORRECTED TO 1.2 m

(MELVILLE BOW)



Friction test program ; Ice sheet #1 and #2
Data corrected for thickness and strength
Target ice thickness = 1.2 m
Target ice strength = 500 kPa
Friction coefficient = 0.06
Thickness correction factor = 1.4

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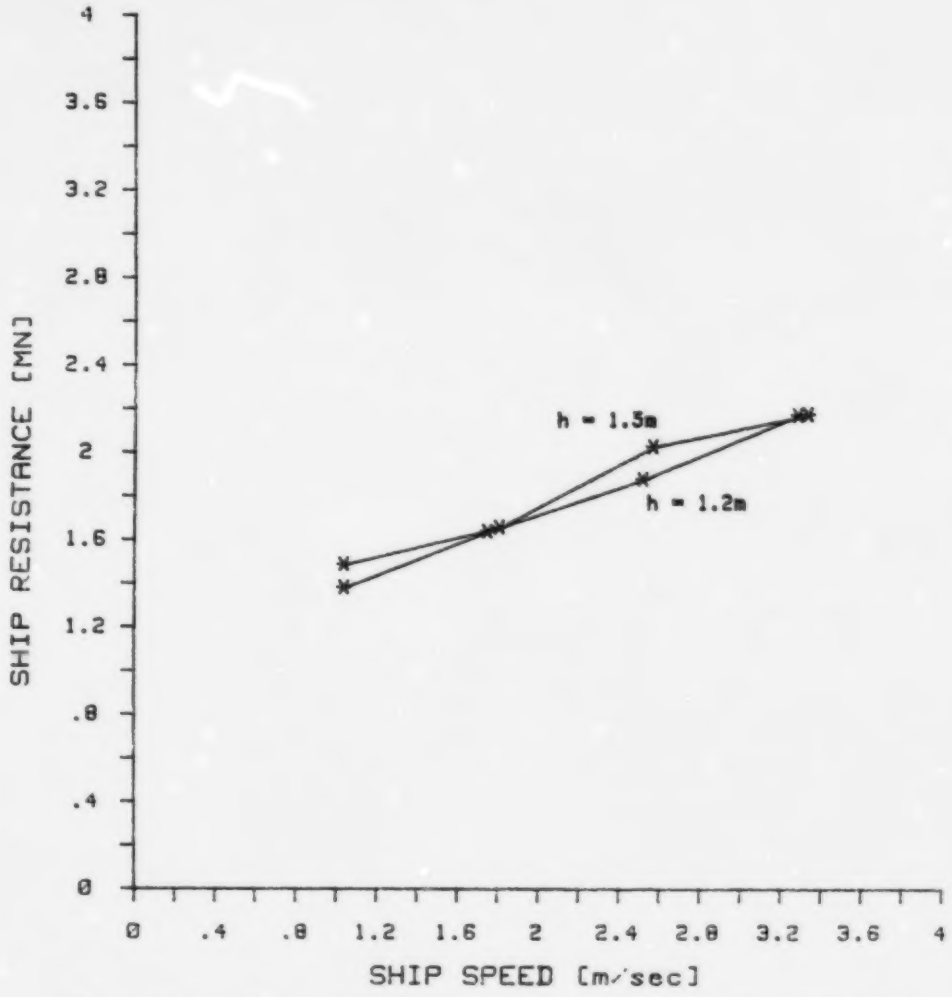
FIGURE 3.16

FULL SCALE RESISTANCE vs SPEED FOR A RANGE OF THICKNESS CORRECTED TO 1.2 m

(MELVILLE BOW)



Friction test program ; Ice sheets #1 and #2
Data corrected for thickness and strength
Target ice thickness = 1.2 m
Target ice strength = 500 kPa
Friction coefficient = 0.06
Thickness correction factor = 1.25

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3.3 Strength Variation

Throughout the midbody program every level ice test was repeated with a presawn test. This permits an analysis of the variation of ice strength at that particular speed and ice condition. Although some correlation has been observed between presawn tests and the strength of the level ice sheet in which the test was initiated, this correlation is considered to be very weak and, for the purposes of adjusting data to target strengths, is ignored.

However, the results of this test program indicate that there may be limitations to this method that have not been identified before. Formerly, it had been assumed that, as the ice strength reduced, there would be a constant reduction in the measured resistance to the presawn value at zero strength. This has been the basis for the analysis of many model and full scale tests.

During the second, and some subsequent runs, the ice sheets were tested with ice strength values down to 10 kPa. This was not intentional and resulted from problems with the cooling system in the ice tank. The results from these low strength tests were not lower resistances, as may be expected, but in most cases, higher resistances. This implies an inflection in the resistance versus strength curve at low ice strengths resulting in the same or higher resistances as ice strength is reduced.

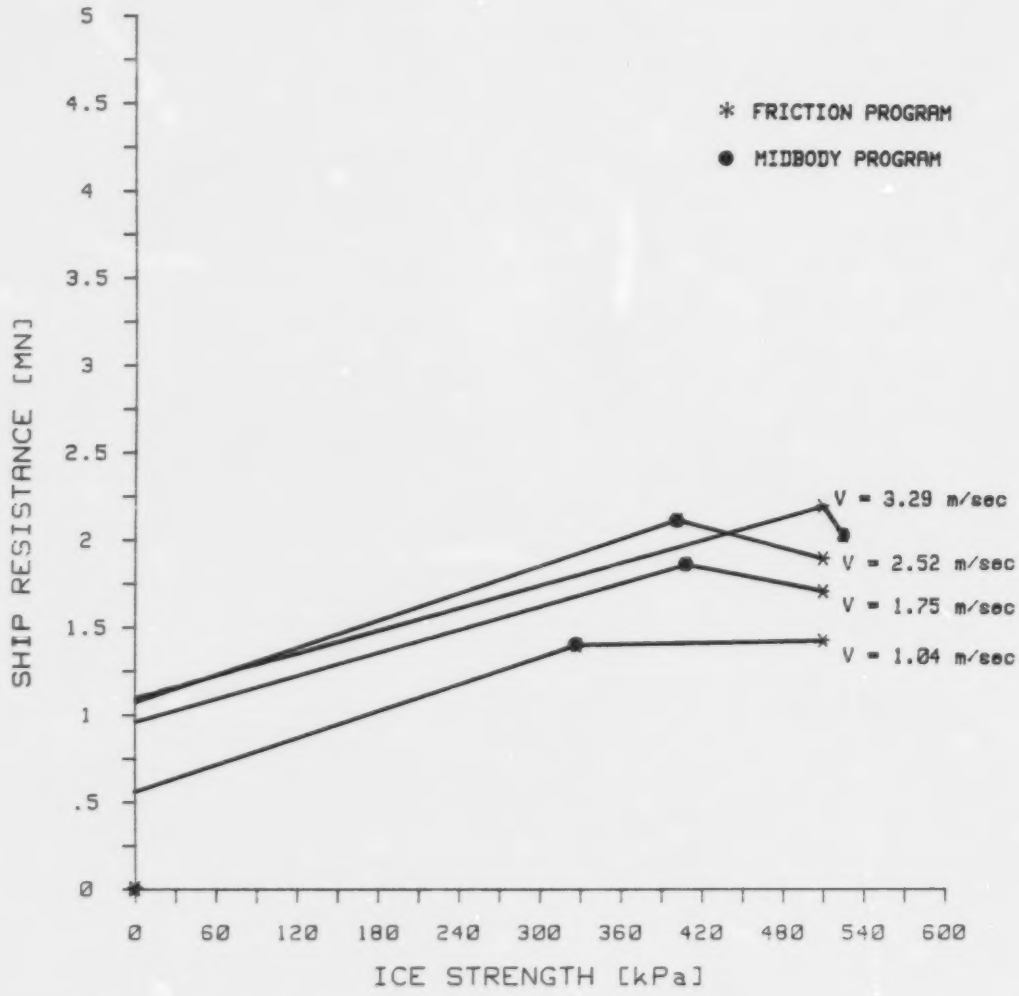
A similar phenomenon has been observed with the elastic modulus which, at lower values, produces higher resistances due to the energy absorption and additional ice bending due to the more plastic ice failure. The ratio of flexural strength and modulus (E/Sigma) for the first ice sheet was 1,775 and corresponded to an average flexural strength of 23 kPa. The E/Sigma for the second test was about 1,202 and the average flexural strength was 13.8 kPa. Although the second ice sheet had a lower E/Sigma value than the first, from our experience it is still well within the acceptable range of this ratio. Unfortunately, since the elastic modulus tests were only conducted before the tests in one location, no conclusions can be drawn that would confirm that low modulus values caused the resistance upturn.

Figure 3.17 presents the full scale resistance versus strength data for the 1.2 m ice sheets in the friction and midbody programs. The data has been corrected for the small variations in thickness and the zero strength or presawn tests have been taken from the friction program. It can be seen from this figure that the data does not indicate a consistent reduction in resistance at lower strengths as may be expected, but an increase or level resistance over a range of ice strengths. Unfortunately there is insufficient data to study this phenomenon in any greater detail, and as a result, and based on our past experience the midbody data set is corrected in the subsequent analysis using the presawn ice sheets.

FIGURE 3.17

FULL SCALE RESISTANCE vs STRENGTH FROM THE MIDBODY AND FRICTION VARIATION PROGRAMS

(MELVILLE BOW)



Midbody test program = Ice sheet #2
Friction test program = Ice sheet #2
Data corrected for thickness
Target ice thickness = 1.2 m
Target ice strength = 500 kPa
Friction coefficient = 0.06

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4. DATA ANALYSIS

4.1 General

The data analysis is presented in the following three sections. The analysis conducted may be summarized as;

a) In conjunction with data collected from the friction test program conducted by Melville in 1986/87, the effect of friction on the resistance of the ARCTIC with the Melville bow is analysed.

b) The base model scale was 1:30. This was adjusted both up and down for each model configuration to represent a ship with a displacement equal to 120 percent and 80 percent of the tested ship. Adjusting the scale also changed the ice thicknesses and strengths and these were corrected to 0.9 m and 500 kPa respectively, using the data correction procedure discussed in Section 3.

c) The model tests are presented as a series of length to breadth ratio tests with each model configuration adjusted to a constant displacement. To accomplish this the scale of each model was adjusted so that they all represented ships of the same displacement. For the purpose of this analysis the existing configuration of the ARCTIC has been selected as the base case ship. The remaining model configurations have been assigned a scale ratio that will result in full scale ships equal in displacement to this base case ship.

It should be noted that, in the analysis undertaken in items b) and c), there has been no account taken for the variation of the ships draught which will change as a function of scale. No correction procedure is known to Melville that would permit a correction for these differences. As a result, the relationships described in these sections should only be used recognising that these differences do exist and may or may not be significant.

4.2 Resistance vs Friction

A series of model tests were conducted as part of the midbody length series to investigate the friction phenomenon. This work was initiated in an earlier study conducted by Melville for TDC (Melville 1987). The midbody program was designed to achieve two objectives related to the friction research;

a) Test a high friction coefficient surface on the present configuration of the ARCTIC to compliment the earlier friction test program.

b) Based on the short ship configuration, test a range of friction coefficients that will compliment the existing data available from the friction program, and permit a comparison between the influence of the midbody friction coefficient and the influence of the midbody length.

These are discussed in the following paragraphs.

a) Tests on the present configuration of the ARCTIC

The results of the friction coefficient variation over the whole model are shown in Figure 4.1. It can be seen from the figure that the increased friction from 0.06 to 0.33 results in a significant rise in the resistance. Most noticeable is the speed dependency of the 0.33 friction coefficient line.

One of the primary conclusions of the original friction program was that the influence of the midbody friction coefficient was very low. Figure 4.2 compares the result from the tests with the full hull coated with a friction coefficient of 0.33 and the result from; the bow coated with 0.33 and the midbody with 0.06: The whole model coated with 0.06 and; the bow coated with 0.06 and the midbody coated with 0.004. It can be seen that the full hull 0.06 test is indistinguishable from the test with 0.06 on the bow and 0.004 on the midbody. This is not the case for the high friction coefficient test in which the smoother midbody appears to have a significant effect.

This comparison may also be made based on a presawn data analysis. Unfortunately, during the original friction program the test associated with the 0.06 friction coefficient on the full hull did not include presawn tests. However, during the original friction test program another surface was tested (surface 3) and found to be indistinguishable from the 0.06 surface. Using the results from the tests it is possible to present the presawn data, as shown in Figure 4.3. These show that there does not appear to be a different relationship between the presawn and level ice tests with the 0.06 and 0.004 friction coefficients. However, there is a significant difference between the presawn and level ice tests for the rough model. During the level ice tests there was a significant resistance difference between the data collected from the test with the rough bow with and without a rough midbody. During the presawn tests the difference is not significant and appears to display a similar relationship as the data collected from the 0.06 and 0.004 test data.

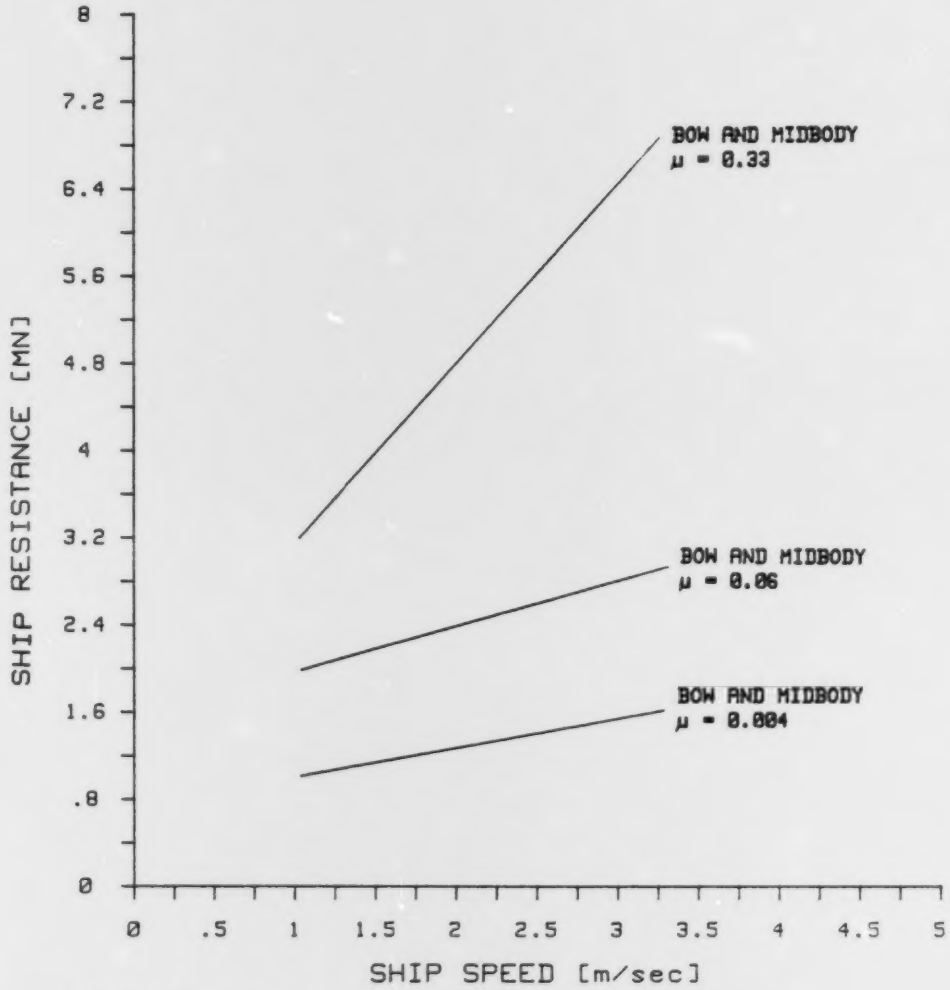
This result would indicate that the influence of the friction coefficient at the high friction values is strongly associated with the breaking component of resistance and is also influenced by speed.

Figure 4.4 presents the friction comparison as resistance versus the logarithm of friction coefficient. The data shows that a change of friction coefficient from 0.06 to 0.004 results in a level ice resistance decrease of 47 percent for the 1 m/sec tests and 43 percent at 3 m/sec. The presawn values are similar, ranging from 46 percent at the lower speed to 39 percent at the higher speed. Changing the friction coefficient from 0.06 to 0.33 results in a level ice resistance increase of 64 percent at the lower speed to 129 percent at 3 m/sec. The presawn tests yield 105 percent and 95 percent for the low and high speeds respectively.

FIGURE 4.1

FULL SCALE RESISTANCE vs SPEED OVER A RANGE OF FRICTION COEFFICIENTS

(MELVILLE BOW)



Midbody test program ; Ice sheet # 4
Friction test program ; Ice sheet #1 and #5
Data corrected for thickness and strength
Target ice thickness = 1.5 m
Target ice strength = 500 kPa

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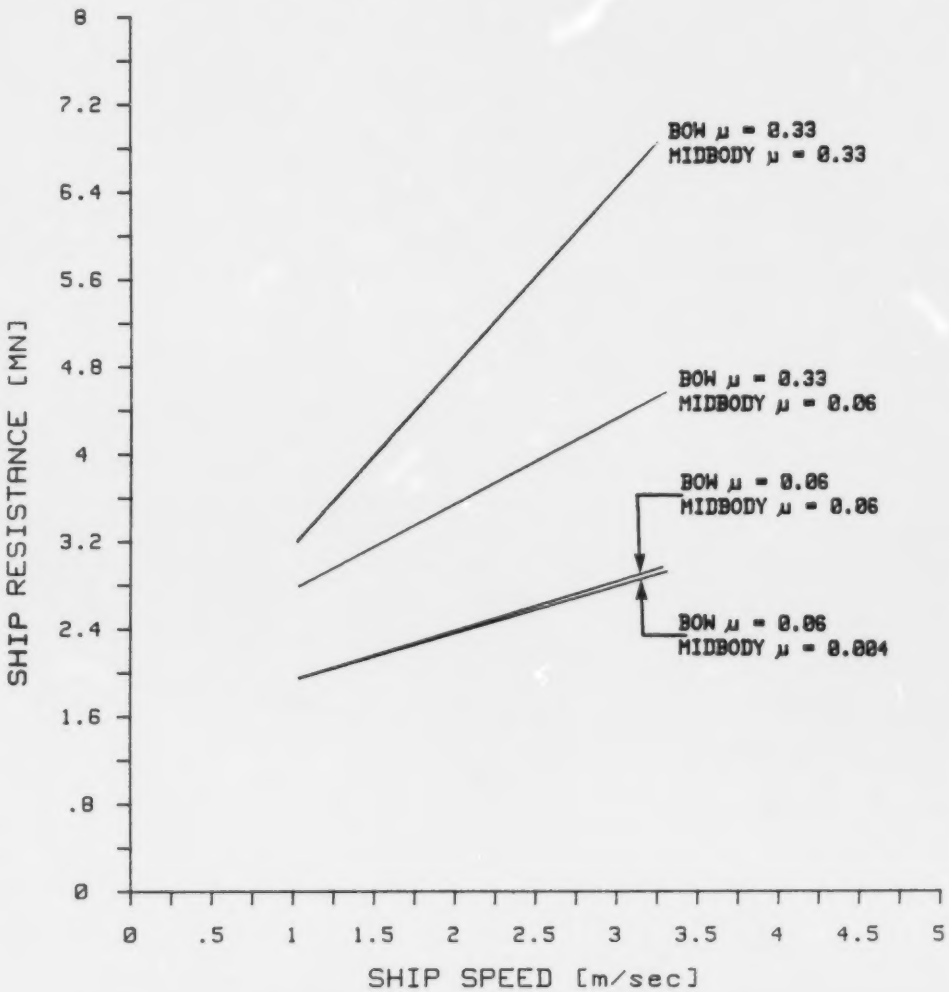
FIGURE 4.2

FULL SCALE RESISTANCE vs SPEED OVER A RANGE OF FRICTION COEFFICIENTS

(MELVILLE BOW)



Midbody test program ; Ice sheet #4
Friction test program ; Ice sheet #1 #7 and #12
Data corrected for thickness and strength
Target ice thickness = 1.5 m
Target ice strength = 500 kPa

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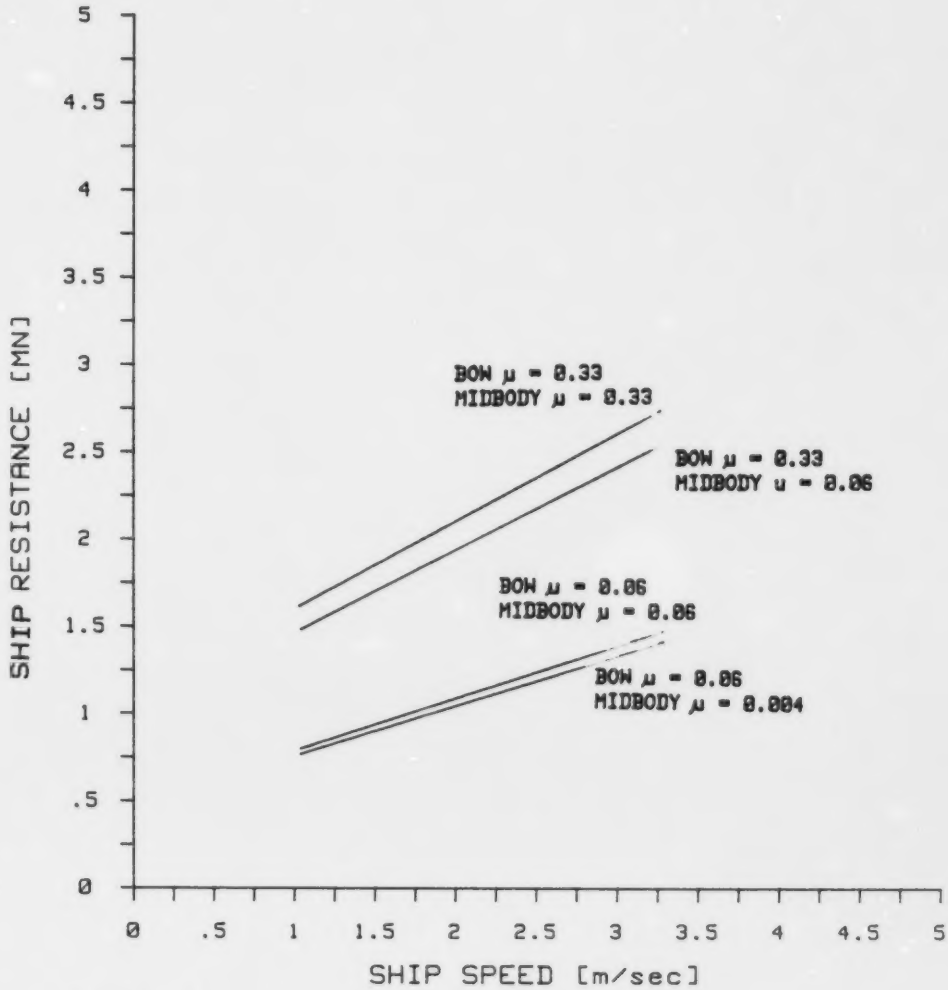
FIGURE 4.3

FULL SCALE PRE-SAWN RESISTANCE vs SPEED OVER A RANGE OF FRICTION COEFFICIENTS

(MELVILLE BOW)



Midbody test program ; Ice sheet #4
Friction test program ; Ice sheet #7 #8 and #12
Data corrected for thickness and strength
Target ice thickness = 1.5 m
Target ice strength = 500 kPa

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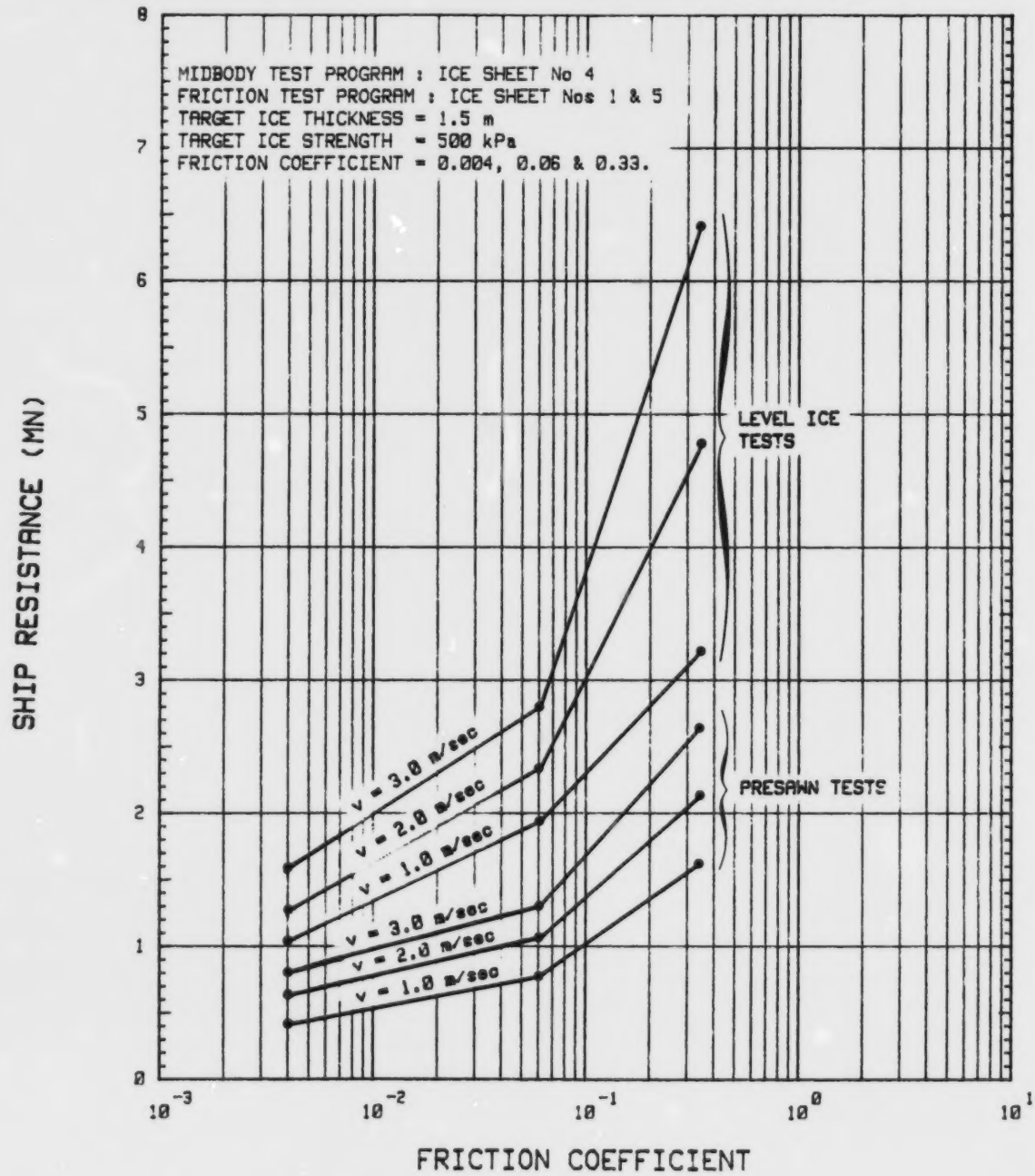
FIGURE 4.4

RESISTANCE VERSUS FRICTION COEFFICIENT FOR THE ARCTIC WITH THE MELVILLE BOW OVER A RANGE OF SPEEDS



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Sample testing has demonstrated that the friction coefficient of smooth sample surfaces tend to be independent of speed and the friction coefficient of rougher surfaces tend to reduce with speed (Forland 1985). This was not found to be true for this model test series which resulted in a reducing speed dependency for the smooth surface and an increasing dependency for the rough surface. The reason for this difference is probably the influence of other factors which have smothered the friction coefficient effects, for example, the different breaking and cusping patterns at higher speeds and the hydrodynamic turbulence caused by the turning floes. The results are summarised in Table 4.1.

b) Tests on the short model of the ARCTIC

The second series of friction tests conducted as part of the midbody program investigated the influence of friction on the short model of the ARCTIC with its Original bow and the Melville bow. Figure 4.5 shows the results of this program for the Melville bow and Figure 4.6 for the Original bow. In the case of the Melville bow there is a rise of resistance with friction coefficient and, this may have been anticipated.

Figure 4.6 presents a significantly different relationship for the Original bow which would indicated that the model coated with the 0.06 friction coating has a higher resistance than the model coated with the 0.33 friction coefficient. These two tests were in ice sheets #10 and #6 respectively. The #6 ice sheet, associated with the 0.33 friction coefficient had one slightly low ice strength point but otherwise resulted in a relatively consistent set of data, as illustrated in Figure 2.6. The #10 ice sheet had one low ice strength and resulted in the erratic relationship discussed in Section 2 and Appendix C. Since an important objective of this project is to present the relationship between friction coefficient and hull form, to have any value to the designer, these trends must be consistent with our fundamental understanding of these relationships. Therefore, on the basis that high values of resistance will occur due to higher friction coefficients either the data associated with the #6 or the #10 ice sheet is incorrect.

Figure 4.7 presents the results from the Original bow tests on logarithmic and linear scales. These tests are also in sharp contrast to the tests of the Melville bow presented in Figure 4.4 and graphically present the downturn in resistance at the higher friction coefficient. As discussed above it is considered that one of these data sets, the 0.06 or the 0.33, is incorrect.

The data associated with the #6 ice sheet and the 0.33 friction coefficient is the most consistent of the two sets, however, comparing this to the 0.33 friction coefficient for the existing Melville bow, Figure 4.8 would lead to a conclusion that, at high friction coefficients, the resistance is independent of bow form, since the data from the Original bow is indistinguishable from the Melville bow.

Figure 4.9 presents the same data from the presawn ice sheets and exhibits a similar trend. However, as discussed in Appendix C, the presawn data from ice sheet 10, the 0.06 friction coefficient test, did not exhibit the erratic trend of resistance with speed, and the trend exhibited in

TABLE 4.1

PERCENTAGE VARIATION OF RESISTANCE WITH CHANGE OF FRICTION COEFFICIENT FOR THE EXISTING SHIP

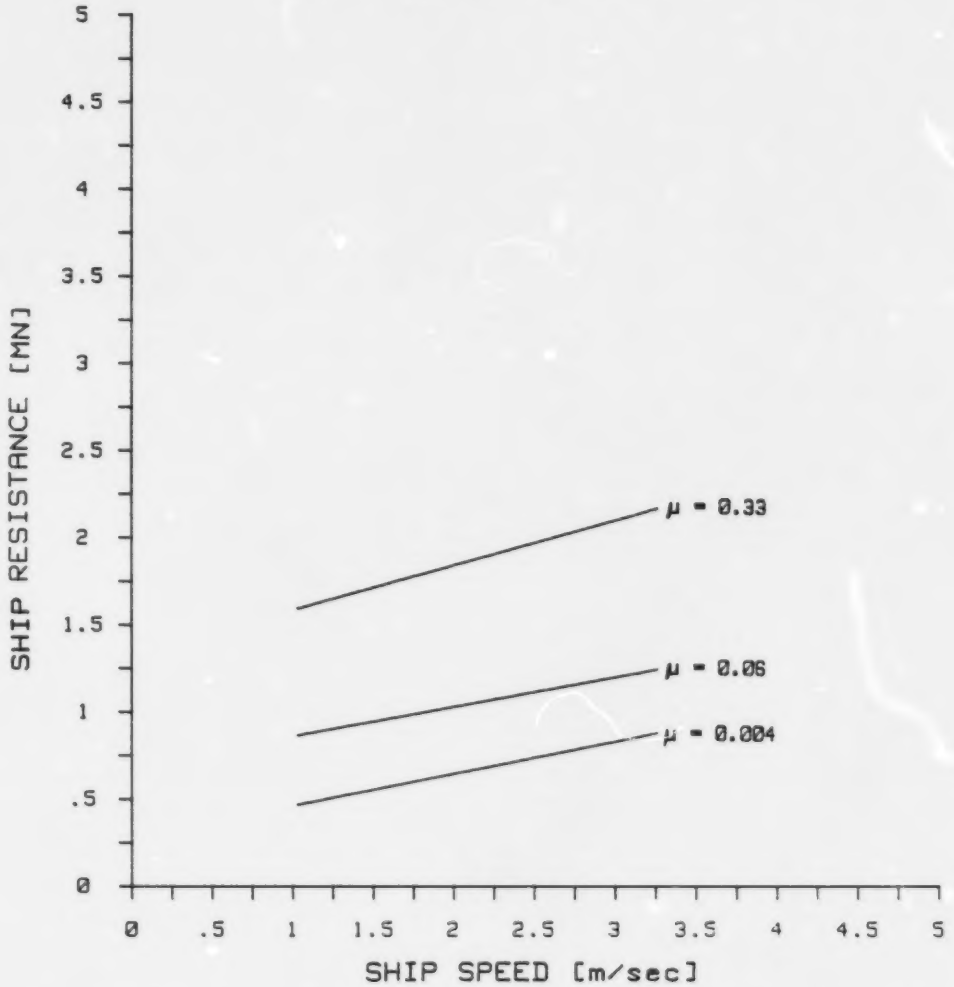
SPEED [m/sec]	LEVEL ICE RESISTANCE [MN] FRICTION COEFFICIENT			% CHANGE	
	0.004	0.06	0.33	DECREASE 0.06 to 0.004	INCREASE 0.06 to 0.33
1	1.03	1.95	3.20	47%	64%
2	1.30	2.36	4.80	45%	103%
3	1.59	2.80	6.42	43%	129%
SPEED [m/sec]	PRESAWN RESISTANCE [MN] FRICTION COEFFICIENT			% CHANGE	
	0.004	0.06	0.33	DECREASE 0.06 to 0.004	INCREASE 0.06 to 0.33
1	0.42	0.78	1.6	46%	105%
2	0.61	1.04	2.1	41%	102%
3	0.81	1.33	2.6	39%	95%

es: Melville Bow on existing midbody length

FIGURE 4.5

FULL SCALE RESISTANCE vs SPEED
FOR A RANGE OF FRICTION COEFFICIENTS

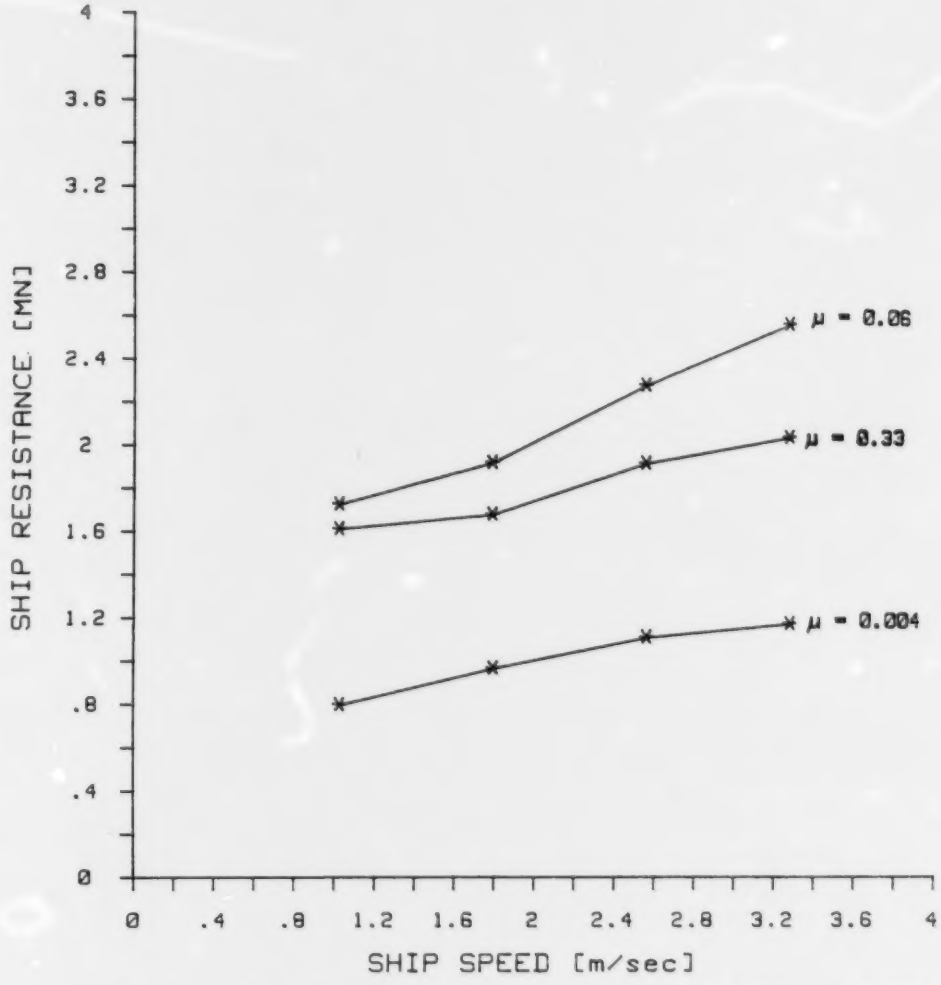
(MELVILLE BOW)



Midbody test program ; Ice sheet #5 #7 and #8
. ; Short ship with Melville bow
Data corrected for thickness and strength
Target ice thickness = 0.9 m
Target ice strength = 500 kPa
Thickness correction factor = 1.25

FIGURE 4.6

FULL SCALE RESISTANCE vs SPEED FOR THE ORIGINAL BOW OVER A RANGE OF FRICTION COEFFICIENTS



Midbody test program ; Ice sheet #6 #9 and #10
Data corrected to target strength and thickness
Target ice thickness = 0.9 m
Target ice strength = 500 kPa
Friction Coefficient = 0.004 0.06 and 0.33
Thickness correction factor = 1.25

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FIGURE 4.7

RESISTANCE vs FRICTION COEFFICIENT FOR THE ORIGINAL BOW OVER A RANGE OF SPEEDS

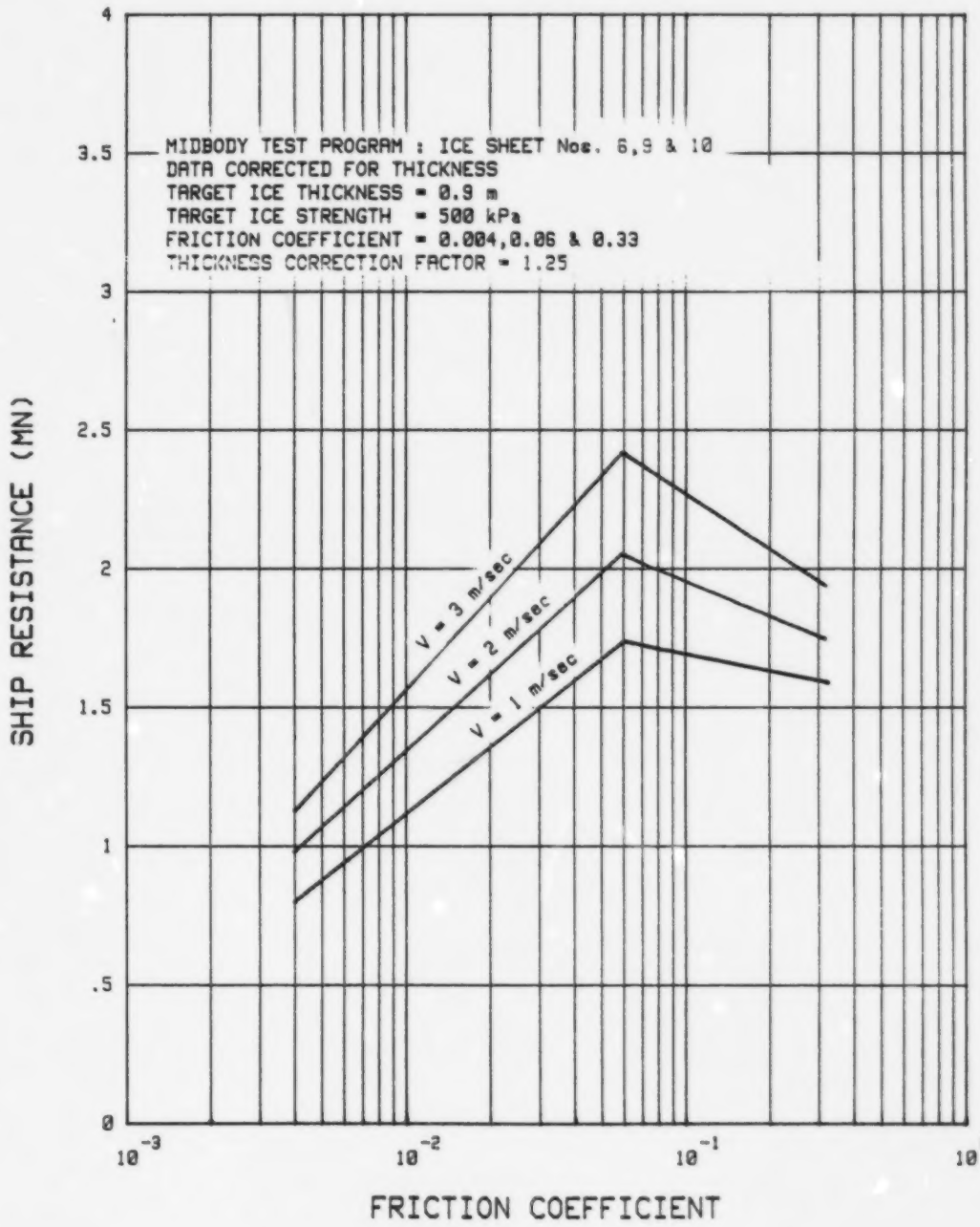

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FIGURE 4.8

RESISTANCE vs FRICTION COEFFICIENT FOR THE MELVILLE BOW OVER A RANGE OF SPEEDS

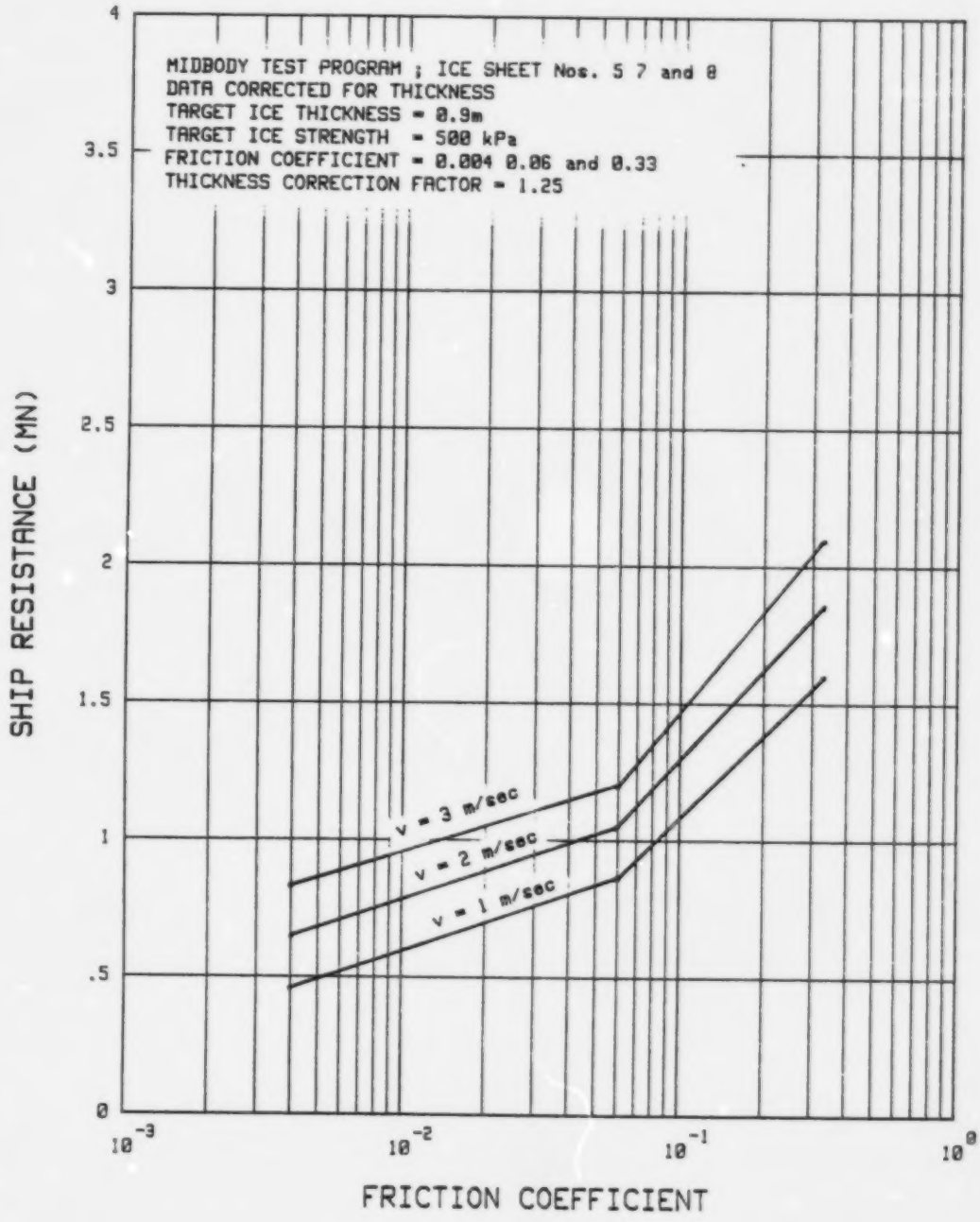

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FIGURE 4.9

PRE SAWN RESISTANCE vs FRICTION COEFFICIENT

FOR THE ORIGINAL BOW OVER A RANGE OF SPEEDS

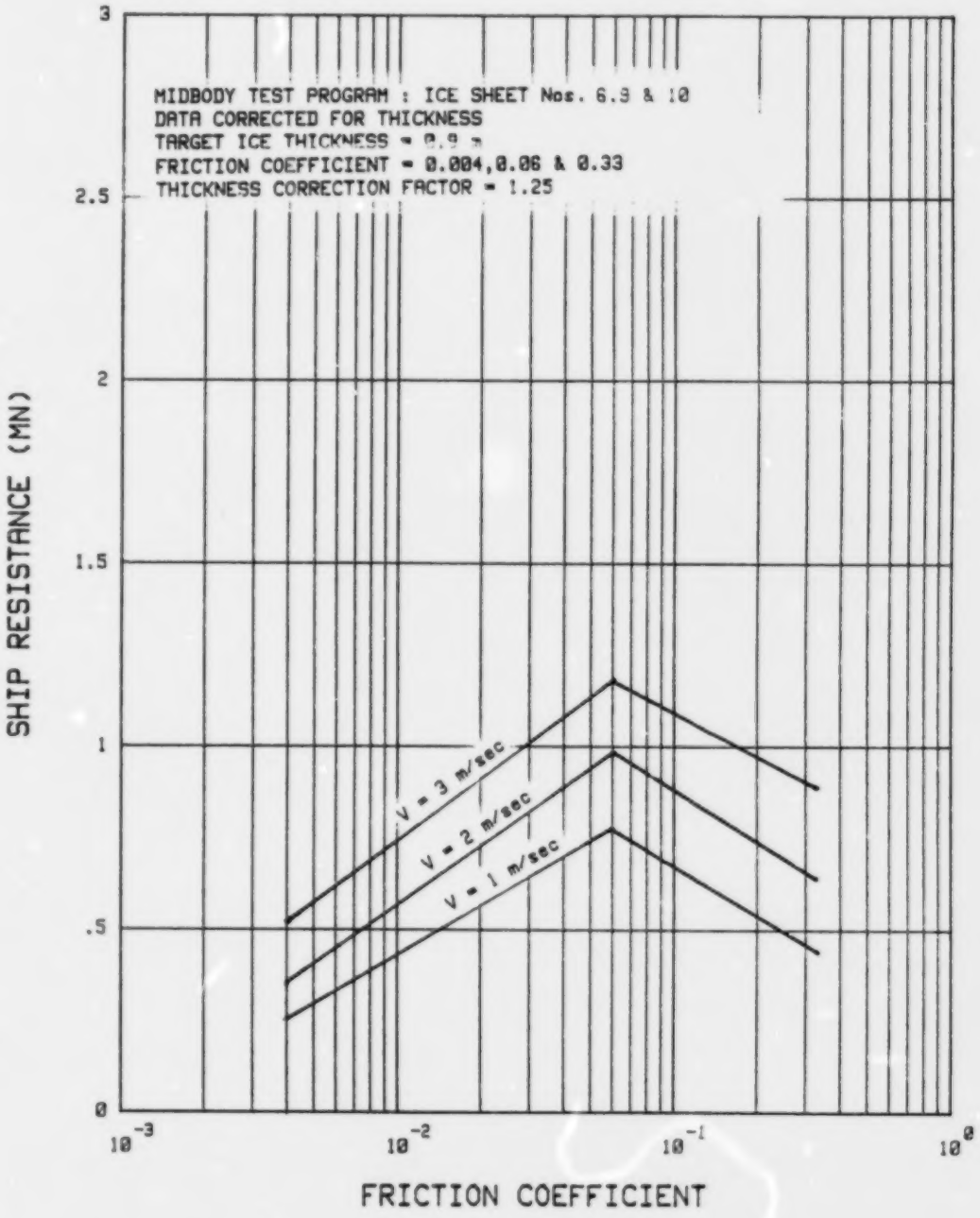

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Figure 4.9, adds some confidence that the test #10, with 0.06 friction coefficient is correct. This leads to our conclusion that, based on this data, the results from the 0.33 test are considered questionable and there is limited confidence in the 0.06 friction test data.

Since no addition friction data is available for the Original bow it is not possible to derive, with any confidence, a relationship between friction coefficient and resistance above 0.06 for the Original bow. In addition, although the trend from 0.004 to 0.06 is characteristic of the relationships seen in other tests, it is based on questionable data.

Figure 4.8 presents the data of the short ship, and Melville bow as resistance versus log friction coefficient. These results are compatible with the relationship established from the existing length of ship and shown in Figure 4.4. Table 4.2 presents the percentage change in resistance between the different friction coefficients for the short ship and may be compared with Table 4.1 which presents the same data for the existing length of ship, fitted with the Melville bow.

Figure 4.10 presents the data from both the Melville bow series and the Original bow series of tests.

It is interesting to compare Table 4.1 with Table 4.2 and note that the relative increases and decreases in percentage change as a function of speed are the same for the short and existing ship lengths, with the exception of the existing ship percentage change of level ice resistance from 0.06 to 0.33. All the percentage changes, with the exception of this set, reduce as a function of speed. This may have been anticipated from the sample friction tests which indicate that the friction forces for a smooth material on ice, became less sensitive to speed as the speed increases. The exception to this trend, noted above, represents an upward trend of over 65% between the low and high speed data and is more representative of the trend that would be observed if the ice moved over a material. This may suggest an interesting basis for the assumption that the effective friction coefficient seen by a hull form is representative of ice sliding on a material, rather than the material sliding on ice.

4.3 Resistance vs Length

The primary objective of this test program was to investigate the influence of length on the icebreaking resistance. Four length variations were tested using the Melville bow and three length variations with the Original bow, as described in Section 2. The tests, and comparison are all conducted at an ice thickness equivalent to 0.9 m. Figure 4.11 presents a schematic of the models tested, and their relative lengths.

Figure 4.12 presents the results of the tests for three speeds as resistance versus length for the Melville bow form.

It can be seen from Figure 4.12 that the slope of the resistance versus length curve increases as a function of ship speed. It may be shown from Figure 4.12 that, at low speeds, a 20 percent increase or decrease in

TABLE 4.2

PERCENTAGE VARIATION OF RESISTANCE WITH CHANGE OF FRICTION COEFFICIENT FOR THE SHORT SHIP

SHORT SHIP

SPEED [m/sec] V	RESISTANCE μ = 0.004 (MN)	RESISTANCE μ_1 0.06 (MN)	% CHANGE μ = 0.06 - 0.004 (DECREASE)	RESISTANCE μ_2 0.33 (MN)	% CHANGE μ = 0.06 - 0.33 (INCREASE)
Original Bow					
1	0.80	1.74	-54%	-	-
2	0.98	2.05	-52%	-	-
3	1.13	2.42	-53%	-	-
Orignal Bow (Presawn)					
1	0.25	0.77	-68%	-	-
2	0.39	0.98	-60%	-	-
3	0.53	1.19	-55%	-	-
Melville Bow					
1	0.47	0.86	45%	1.60	86%
2	0.65	1.05	38%	1.85	76%
3	0.83	1.20	31%	2.10	75%
Melville Bow (Presawn)					
1	0.14	0.43	67%	0.63	47%
2	0.31	0.68	54%	0.94	38%
3	0.49	0.92	47%	1.24	35%

FIGURE 4.10

RESISTANCE vs FRICTION COEFFICIENT FOR THE MELVILLE AND ORIGINAL BOW OVER A RANGE OF SPEEDS

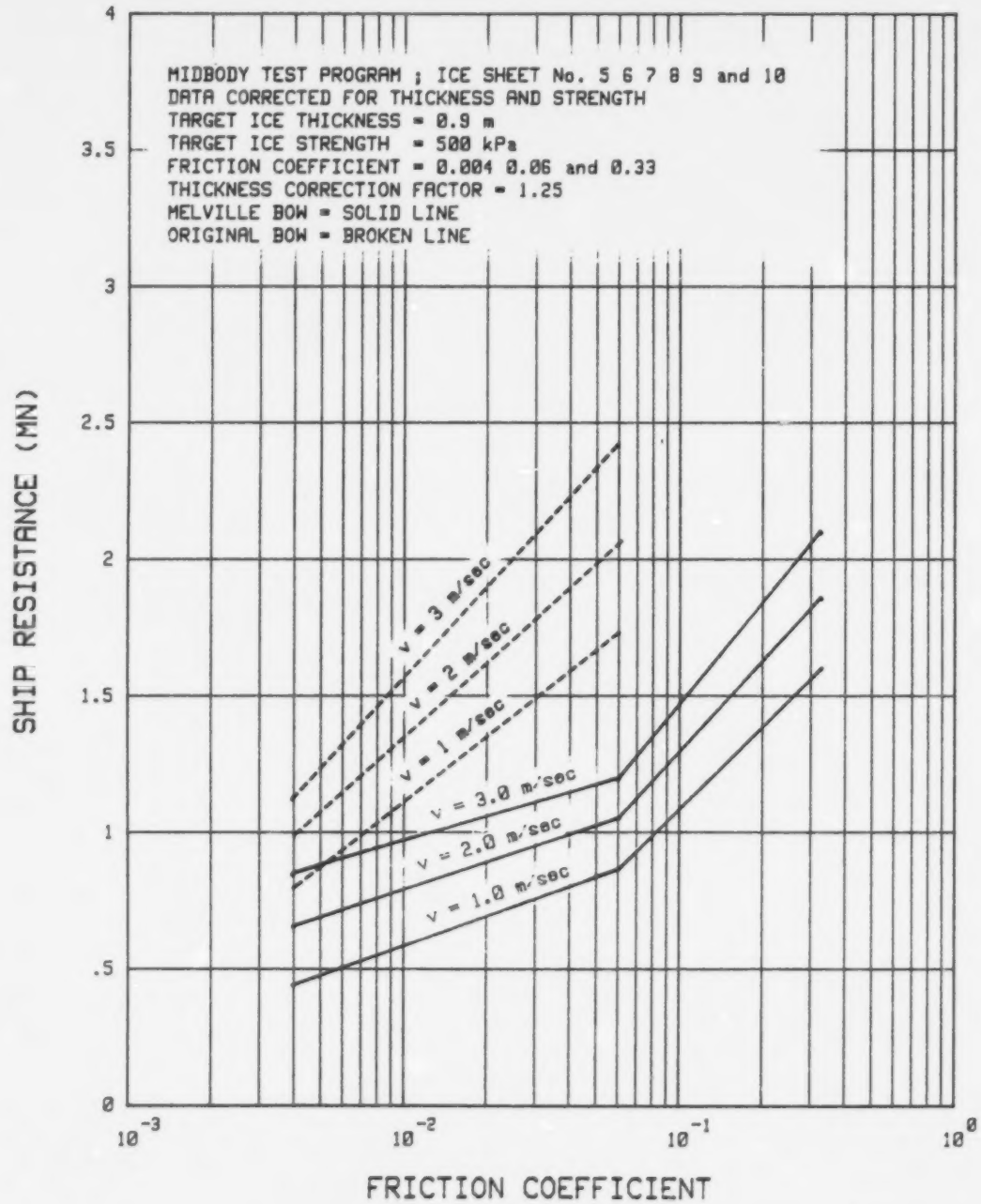

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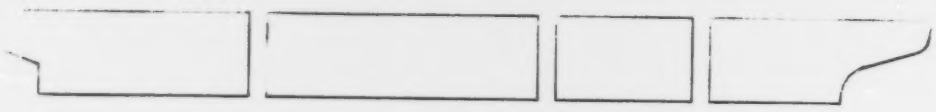
FIGURE 4.11

SCHEMATIC OF MODELS TESTED DURING THE MIDBODY LENGTH VARIATION SERIES



L/B = 11.25 (Melville Bow)
L/B = 10.83 (Original Bow)

L/B = 8.99 (Melville Bow)
L/B = 8.58 (Original Bow)

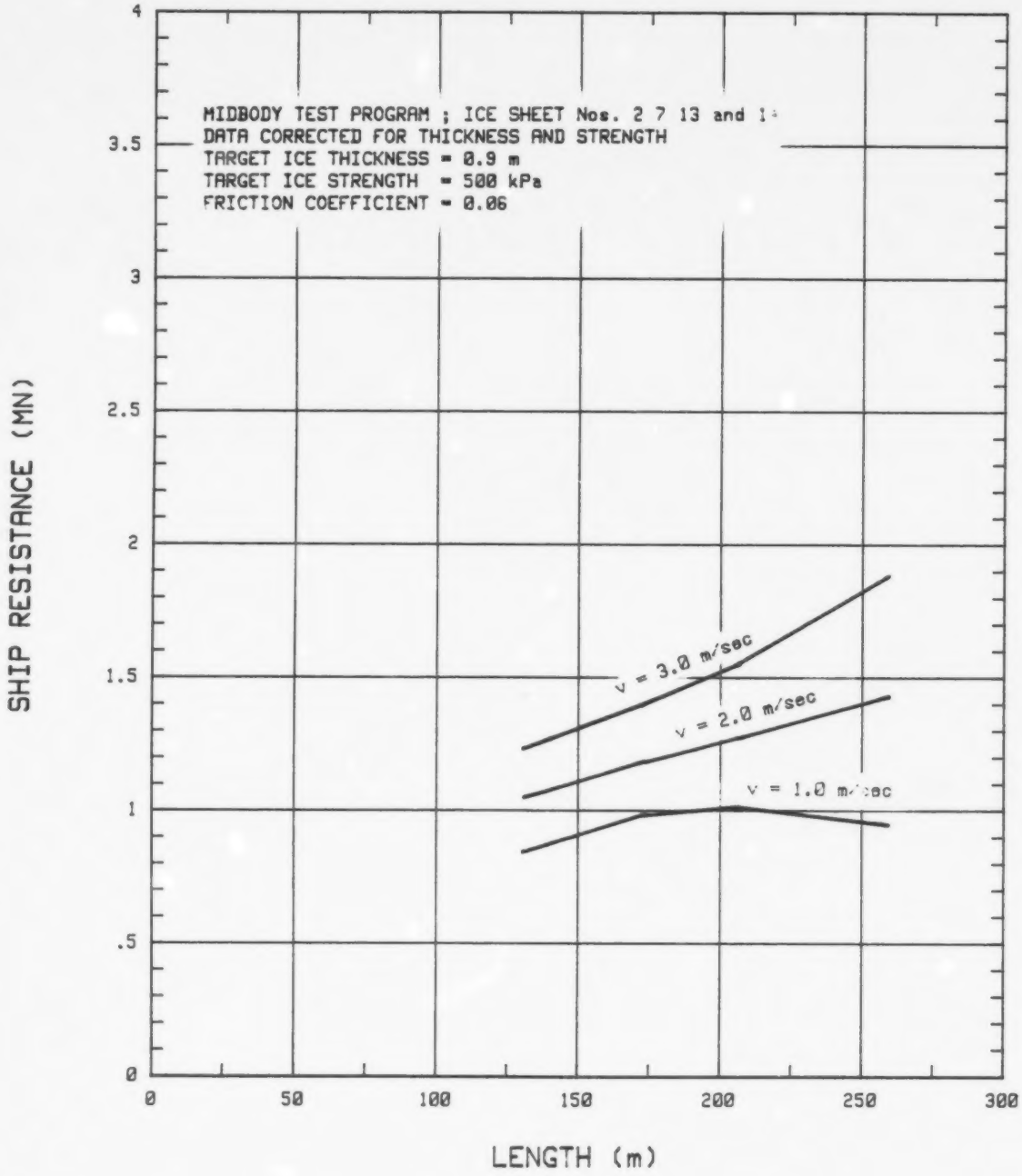
L/B = 7.50 (Melville Bow)

L/B = 5.83 (Melville Bow)
L/B = 5.41 (Original Bow)

- The Models are shown with the Melville bow

FIGURE 4.12

RESISTANCE vs LENGTH FOR THE MELVILLE BOW
OVER A RANGE OF SPEEDS



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length from a 206 m long ship will result in about a 5 percent decrease in resistance. At higher speeds of 3 m/sec a similar increase in length will result in an 18 percent increase in resistance, and a decrease in length will result in a 12 percent reduction of resistance.

As with any physical model testing when only a limited number of tests are available it is important to recognise that a single erroneous data set can significantly influence resultant trends. In the case of the Melville bow tests discussed above, the data is consistent and the resultant trend of length, speed and resistance is not unreasonable, especially for the higher speed data. As length increases for a constant beam it may be expected that resistance will increase. The resistance does not increase sharply and this was anticipated due to the results from the friction test program which demonstrated that, with a friction coefficient of 0.06, the midbody was not a significant factor on the resistance. At lower speeds the resistance tends to decrease with length. This was not anticipated since the friction test program resulted in little or no observable speed dependency of resistance with midbody friction variations. Since the resistance reduction is relatively small, the trend seen in Figure 4.12 at the low speed could be due to the range of accuracy associated with ice model testing.

Figure 4.13 present the result from the Original bow tests and were not anticipated. The large difference between the 197 m ship and the shorter and longer ship configurations is not thought to be a reasonable result and has been examined in more detail.

Part of the first analysis task in this project was to assess the overall program and establish a consistent set of data from the tests. However, some of these tests were conducted in ice sheets whose properties were not considered to be within the range for conventional correction procedures (Appendix C). As a result the data was adjusted, in some cases quite significantly, so that it would conform to our present understanding of thickness, strength and resistance relationships. No attempt was made to compare or correct tests on the basis of model configuration or any preconceived understanding of how different models should or should not perform.

However, due to the results from the Original bow discussed above, the data was reviewed again. Figure 4.14 presents the model scale test results, corrected for strength, based on the presawn test results. The strength variation was only considered to be a problem with ice sheet 10 (the short ship) in which a minimum average value of 13 kPa was recorded, associated with the 0.188 m/sec data point and discussed above. The inconsistency of the data from this ice sheet is evident from Figure 4.13.

The observations that may be made from this review and Figure 4.14 are;

a) The short 124 m ship appears to have a lower resistance than the existing 201 m ship although, depending on the influence of the low ice strength data in the sheet, it may be significantly lower or only slightly lower.

FIGURE 4.13

RESISTANCE vs LENGTH FOR THE ORIGINAL BOW
OVER A RANGE OF SPEED

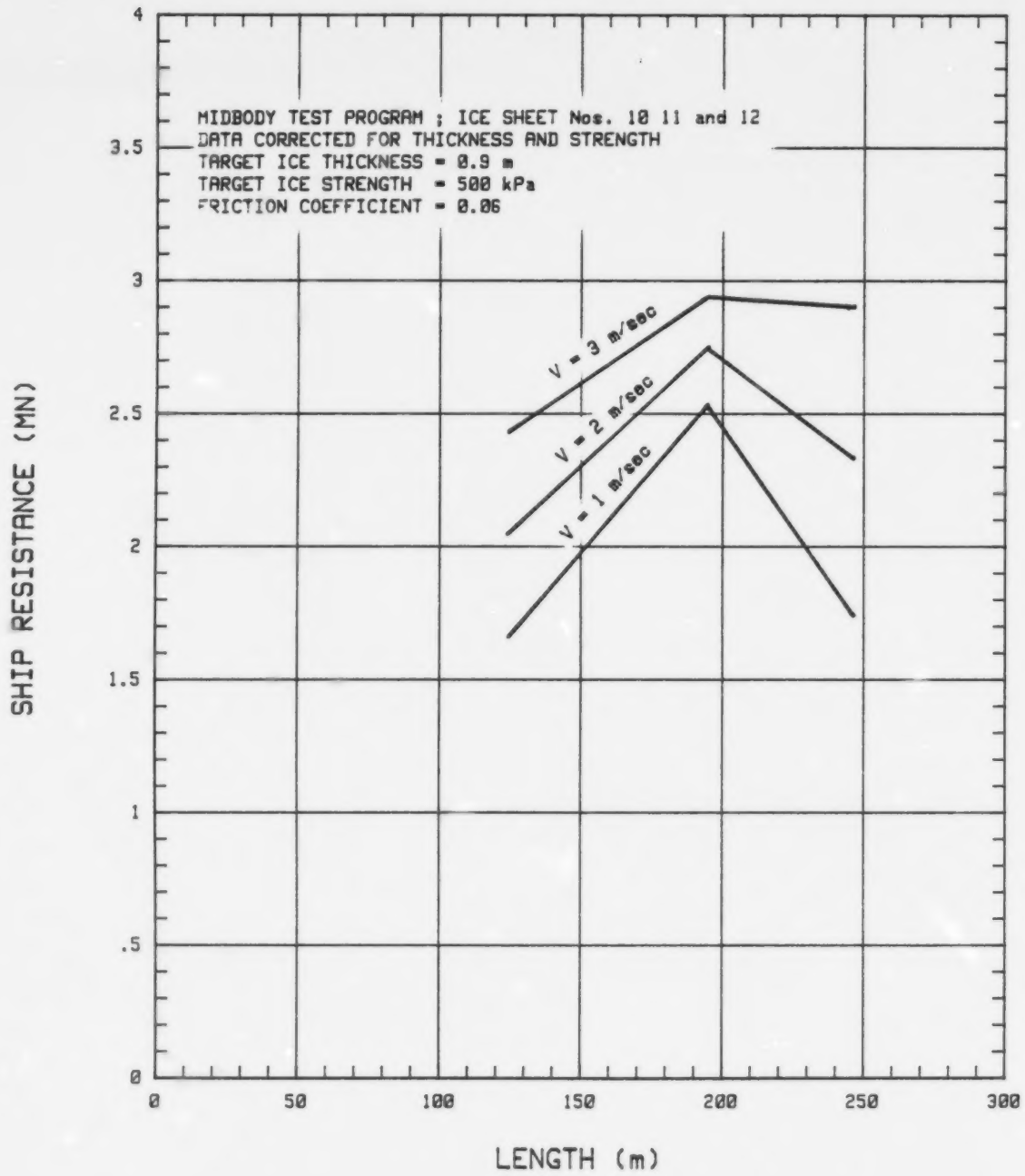

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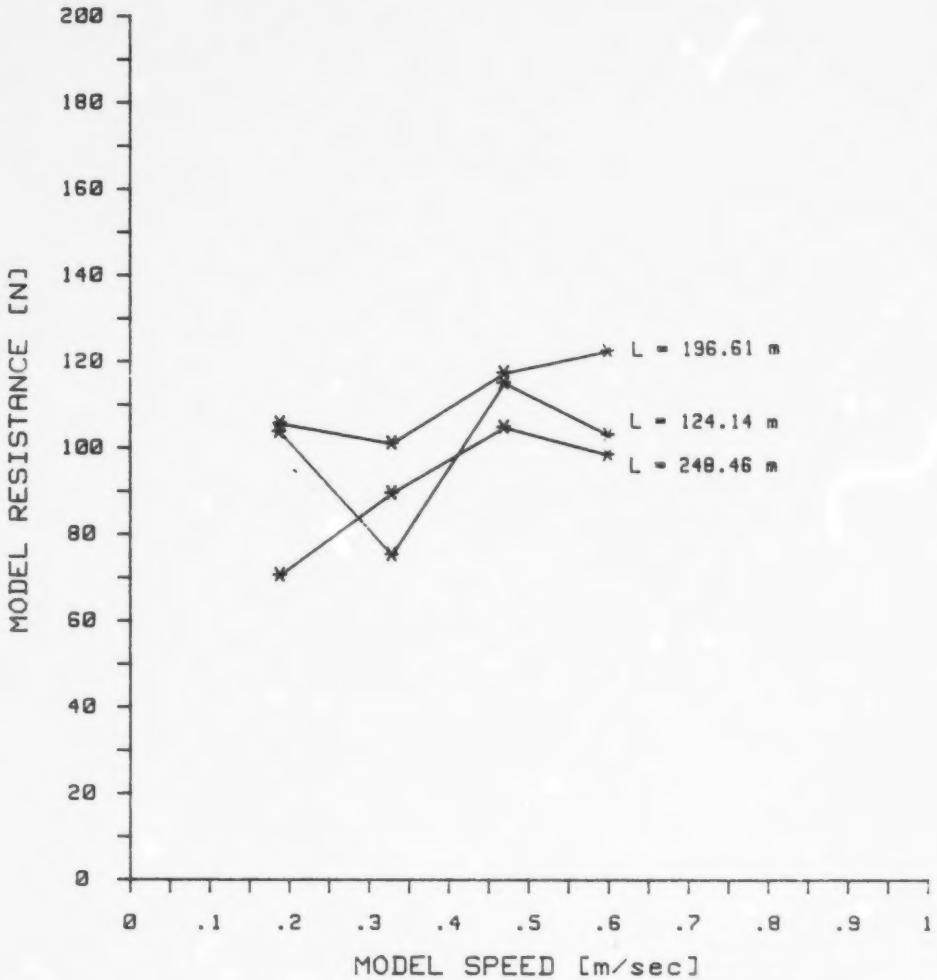
FIGURE 4.14

MODEL SCALE RESISTANCE vs SPEED FOR
THE ORIGINAL BOW OVER A RANGE OF LENGTHS



Midbody test program ; Ice sheet #10 #11 and #12
Data corrected to target strength and thickness
Target ice thickness = 0.03 m
Target ice strength = 19 kPa
Friction Coefficient = 0.06

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b) The resistance data collected for the existing 197 m long ship, was only adjusted using conventional procedures and is considered to have been collected under favorable model ice conditions.

c) In Appendix C, the results from the short ship configuration were corrected using the 0.33 and 0.6 m/sec data points and, as a result the corrected data shows the short ship with the lowest resistance. It should be noted however that the 0.188 and 0.47 m/sec data points are indistinguishable from the existing 197 m ship.

d) The interpolation of resistance between the long 248 m ship and the short 124 m ship, results in a full scale performance prediction considerably closer to the known full scale performance of the original 197 m ship than the results of the model tests.

e) By ignoring the results from the original 197 m ship, the percentage rate of change of resistance with length is approximately the same for both hull forms; approximately a 20 percent increase in resistance for the 3 m/sec data and 5 percent increase in resistance for the 1 m/sec data.

f) The relative performance of the three model configurations are the same regardless of how the data is corrected.

The above review does not justify any change in the data analysis presented in Appendix C. However, the results from the Original bow, presented in Figure 4.13, do not conform to our fundamental understanding of how these variables should perform, nor can we offer any explanation for why the experiments should have given these results.

On the bases of these observations it was elected to replace the model test results from the original ship configuration with a linear interpolation between the long and the short models. The results of this decision are presented in Figure 4.15.

The data presented in Figures 4.12 and 4.15 forms the basis for the displacement and L/B relationships discussed in the following sections.

4.4 Displacement Variation

Two modifications to each of the tested model configurations were used to investigate the influence of displacement on the ice resistance.

a) Increasing and decreasing the scale of the model to achieve a +/- 20 percent variation on displacement.

b) Adjusting the scale ratio associated with each model to obtain a series of full scale ships with a constant displacement.

FIGURE 4.15

ADJUSTED RESISTANCE vs LENGTH FOR THE ORIGINAL BOW OVER A RANGE OF SPEED

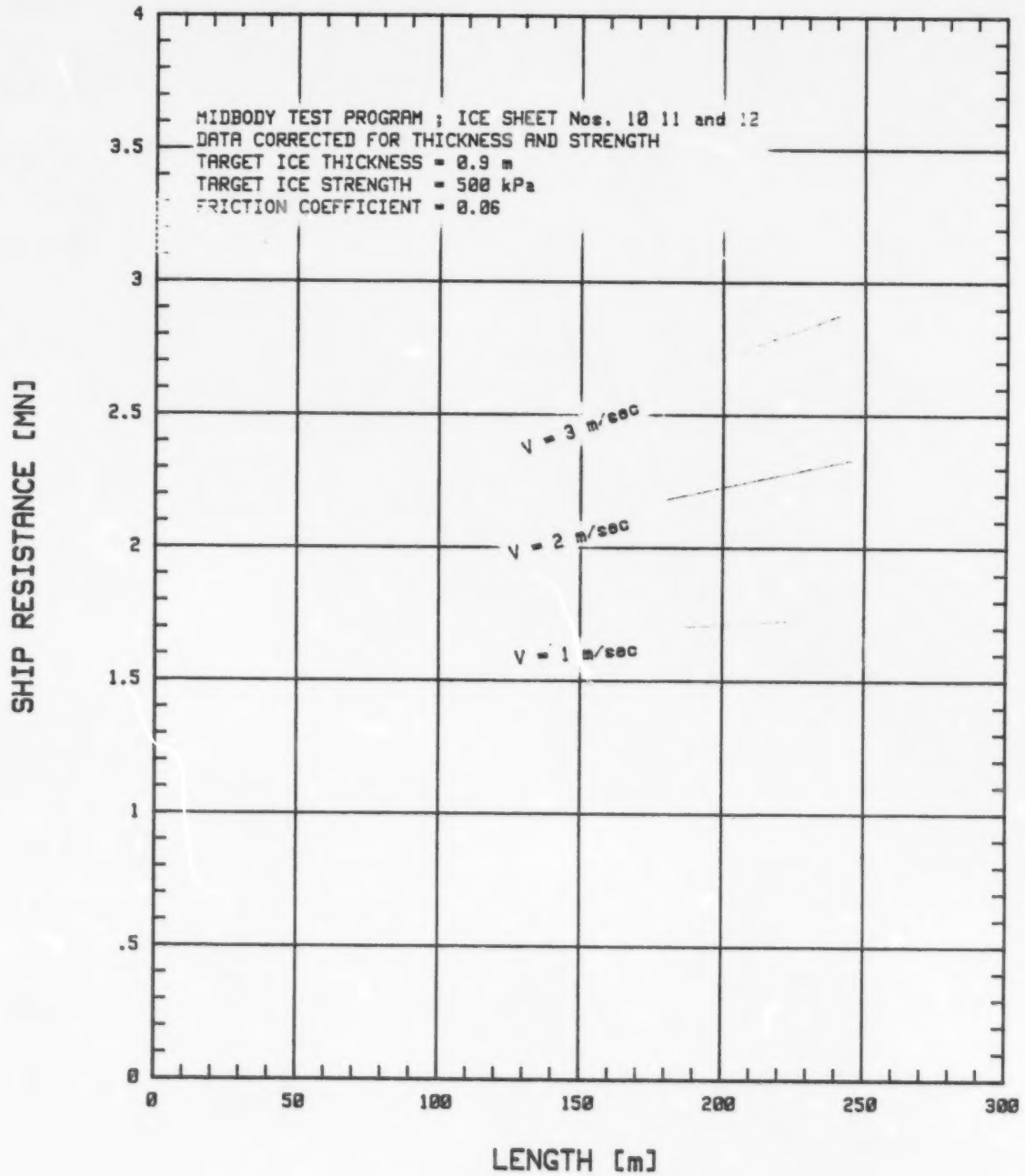

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Table 4.3 summarizes the calculated new scale factors and associated ship sizes for the +/- 20 percent variation analysis. It should be noted that, together with the ship dimensions, the scale adjustment will also change the full scale ice thickness and strength represented by the model ice. As a result, the data had to be corrected to a single ice thickness and strength using the analysis described in Section 3. It was elected to adjust the ice data to an ice thickness of 0.9 m and ice strength of 500 kPa.

The displacement relationship is a function of the scaling laws used to adjust the model resistance and ice properties. To obtain the adjusted value the displacement of the full scale ship, represented by the model, was adjusted by 20 percent. Since displacement will be scaled using the cube of the scale ratio, the scale ratio itself will be scaled to the cube root of 20 percent, or about 6 percent. The ice thickness, strength and ship parameters are all scaled to this linear scale ratio and will have an effect on the resistance which will have to be adjusted for the different ice properties.

Table 4.4 documents the results and Figure 4.16 presents the resistance versus percentage displacement relationship for 2 m/sec. As may be expected, the resistance increases as the displacement increases and decreases as the displacement decreases. The change is about 4 to 7 percent for both the Melville bow and Original bow for a 20 percent change in displacement.

The second manipulation of the model test data was to adjust the scale of each model configuration so that the resultant full scale data is representative of ships with the same displacement. Table 4.5 defines the calculated scale ratios and associated hull parameters. Table 4.6 presents the calculated resistances for a range of speeds that result from the data manipulation.

The results are presented in Figure 4.17 for the Original and Melville bow forms.

As the L/B ratio decreases with a constant displacement the beam will increase. Since it is generally recognized that the beam will have a stronger influence on the resistance than the length, it may be anticipated that resistance will increase with the lower L/B ships.

It should be noted in Figure 4.17 that the L/B value of 8.57 for the Original bow is based on an interpolation from the longer and shorter ships discussed elsewhere in this report.

As may have been expected the Original bow demonstrates an increase of resistance with lower L/B values, although not as strongly as anticipated. Based on constant length and a speed of 1 m/sec the resistance varies proportionally with beam raised to the power of 0.26 for the range above L/B = 8.57 and 0.49 for the range above 8.57. It may be noted that it is generally considered that the resistance will vary proportionally with beam raised to a power of between unity and 1.5.

The results from the Melville bow tests show an even lower resistance dependency on beam.

TABLE 4.3

MATRIX OF DISPLACEMENT COMBINATIONS

	V (m^3)	λ	L (m)	B (m)	V + 20% (m^3)	λ	L (m)	B (m)	V - 20% (m^3)	λ	L (m)	B (m)
MELVILLE BOW												
Long Ship	50,629	30	258.03	22.93	60,755	31.9	279	24.38	40,503	27.9	293.97	21.32
Base Ship	37,668	30	206.16	22.93	45,200	31.9	223	24.38	30,133	27.9	191.73	21.32
Short Ship 2	29,191	30	171.87	22.93	35,029	31.9	187	24.38	23,353	27.9	159.84	21.32
Short Ship 1	19,719	30	133.71	22.93	23,663	31.9	147	24.38	15,775	27.9	124.35	21.32
ORIGINAL BOW												
Long Ship	50,256	30	248.46	22.93	60,307	31.9	269	24.38	40,205	27.9	231.07	21.32
Base Ship	37,294	30	196.61	22.93	44,752	31.9	214	24.38	29,834	27.9	182.85	21.32
Short Ship 1	19,096	30	124.14	22.93	22,915	31.9	136	24.38	15,277	27.9	115.45	21.32

TABLE 4.4

RESULTS OF DISPLACEMENT [illegible]

BOW FORM	L [M]	B [M]	L/B	RESISTANCE [MN] 1m/sec	2m/sec	3m/sec	VOLUME OF DISPLACEMENT [M^3]
Melville +20%	274.37	24.38		0.99	1.48	1.98	60,755
Long Ship -	258.03	22.93	11.25	0.94	1.42	1.88	50,629
-20%	239.97	21.32		0.88	1.33	1.77	40,503
Melville +20%	219.22	24.38		1.06	1.36	1.62	45,200
Base Ship -	206.16	22.93	8.99	1.02	1.28	1.54	37,668
-20%	191.73	21.32		0.95	1.19	1.43	30,133
Melville +20%	187.26	24.38		1.02	1.25	1.48	35,029
Short Ship 2 -	171.87	22.93	7.50	0.98	1.18	1.40	29,191
-20%	159.84	21.32		0.90	1.10	1.29	23,353
Melville +20%	142.18	24.38		0.91	1.12	1.32	23,663
Short Ship 1 -	133.71	22.93	5.83	0.85	1.04	1.22	19,719
-20%	124.35	21.32		0.78	1.95	1.11	15,775
Original +20%	264.20	24.38		1.86	2.47	3.08	60,307
Long Ship -	248.46	22.93	10.84	1.76	2.34	2.91	50,256
-20%	231.07	21.32		1.63	2.19	2.75	40,205
Original +20%	209.06	24.38		2.71	2.93	3.15	44,752
Base Ship -	196.61	22.93	8.57	2.54	2.74	2.95	37,294
-20%	182.85	21.32		2.36	2.54	3.72	29,834
Original +20%	132.00	24.38		1.79	2.19	2.59	22,915
Short Ship 1 -	124.14	22.93	5.41	1.67	2.04	2.43	19,096
-20%	115.45	21.32		1.54	1.90	2.25	15,277

FIGURE 4.16

DISPLACEMENT VARIATION FOR THE ORIGINAL AND MELVILLE BOWS AT 2 m/sec

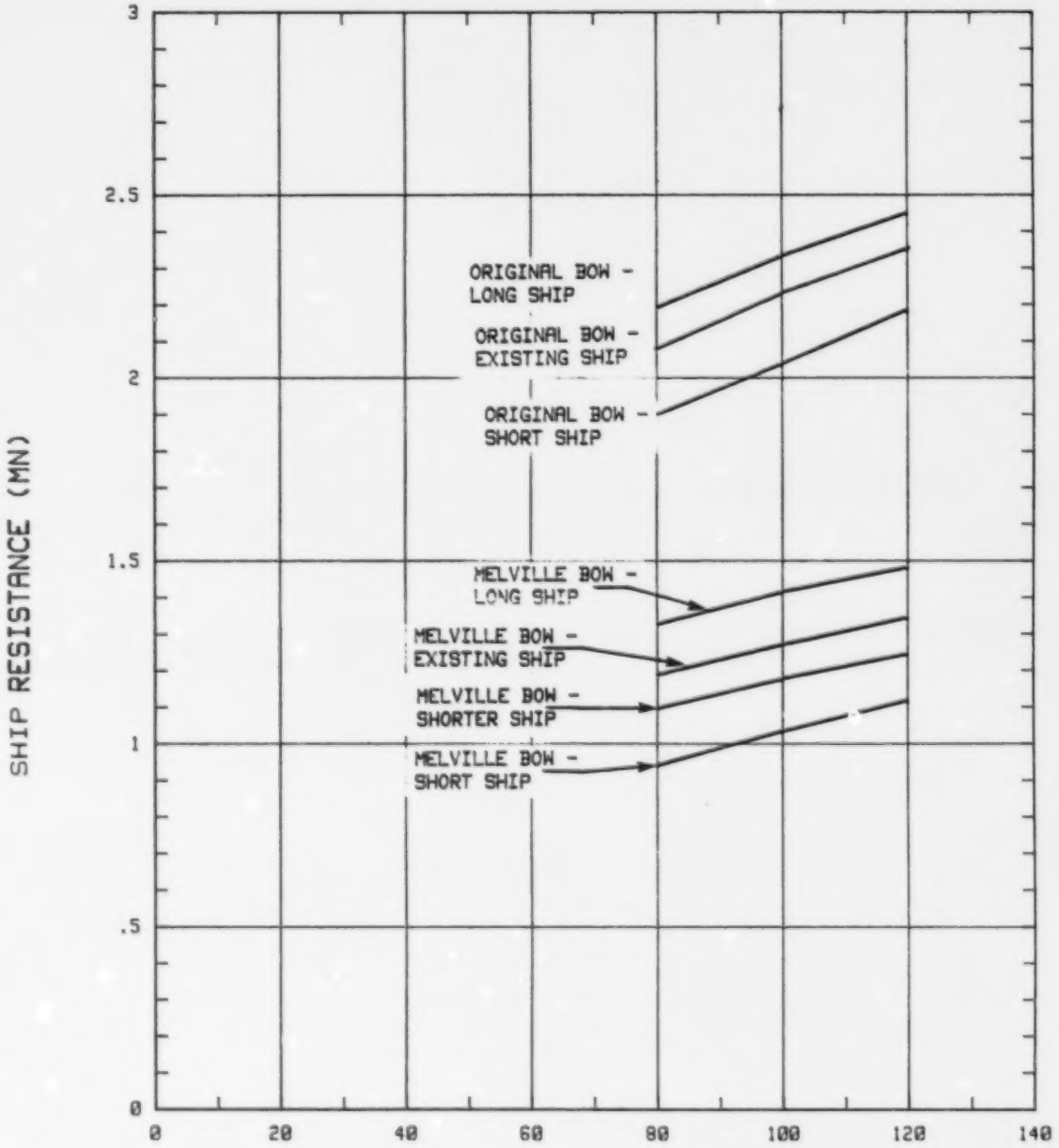

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TABLE 4.5

MATRIX OF DIMENSION COMBINATIONS

	VOLUME OF DISPLACEMENT [m^3]	LENGTH [m]	BEAM [m]	DRAUGHT [m]	L/B RATIO	SCALE FACTOR
MELVILLE BOW						
Long Ship	37,666	233.78	20.77	9.94	11.25	27.18
Base Ship	37,666	206.16	22.93	10.97	8.99	30.00
Short Ship 2	37,666	187.11	24.96	11.94	7.50	32.66
Short Ship 1	37,666	165.80	28.43	13.60	5.83	37.20
ORIGINAL BOW						
Long Ship	37,666	225.68	20.83	9.96	10.83	27.25
Base Ship	37,666	195.95	22.85	10.93	8.58	29.90
Short Ship 1	37,666	155.67	28.75	13.76	5.41	37.62

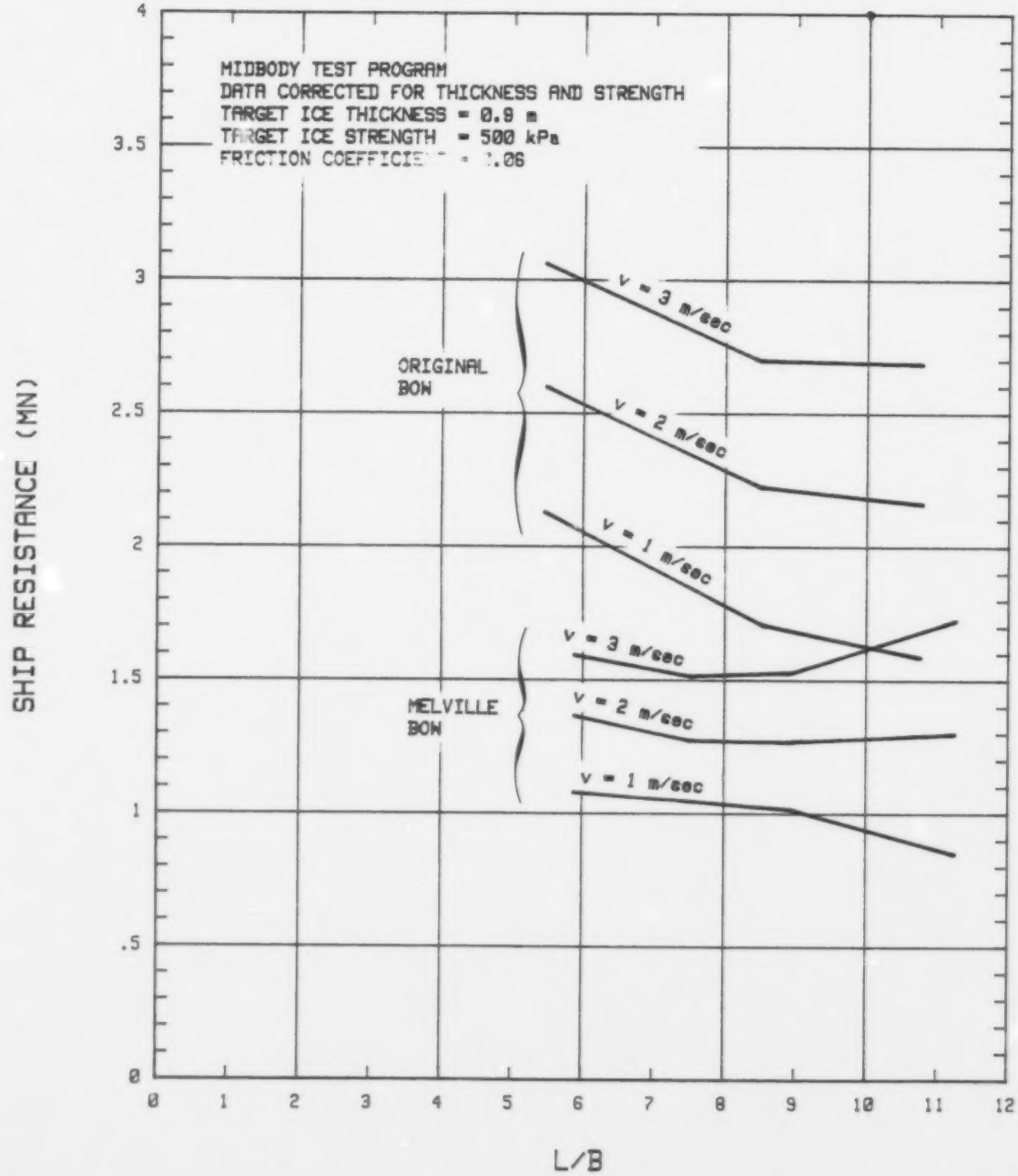
TABLE 4.6

DIMENSION MANIPULATION RESULTS

BOW FORM	λ	LENGTH [m]	BEAM [m]	RESISTANCE [MN] 1m/sec	2m/sec	3m/sec	L/B
Melville Bow							
Long Ship	27.18	233.78	20.77	0.86	1.30	1.73	11.25
Base Ship	30.00	206.16	22.93	1.02	1.28	1.54	8.99
Short Ship 2	32.66	187.11	24.96	1.06	1.29	1.52	7.5[illegible]
Short Ship 1	37.20	165.80	28.43	1.08	1.38	1.60	[illegible].83
Original Bow							
Long Ship	27.25	225.68	20.83	1.60	2.14	2.68	10.83
Base Ship	29.90	195.95	22.85	1.70	2.21	2.70	8.58
Short Ship	37.62	155.67	28.75	2.12	2.60	3.05	5.41

FIGURE 4.17

FULL SCALE RESISTANCE vs L/B RATIO
FOR THE ORIGINAL AND MELVILLE BOWS



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The resistance reduces as the L/B increases for the 1 and 2 m/sec data points. For the 3 m/sec data the resistance reduces from an L/B of 5.83 to 7.7, remains about constant from 7.5 to 8.99 and then increases from 8.99 to 11.25. This result is due to the strong speed dependency observed for the long ship and discussed in another section. From the available data it is not possible to confidently define the L/B dependency. At the lower speeds an L/B increase from 5.83 to 11.25 results in a 20 percent reduction in resistance, at 3 m/sec the L/B increase from 5.83 to 7.5 results in a 5 percent decrease, from 7.5 to 8.99 a 1 percent increase and from 8.99 to 11.25 a 12 percent increase.

An overall trend that may be observed from the data is the overall lower effects of L/B on resistance with higher speeds. For this analysis, since higher L/B ratios result in lower beams, this phenomenon would indicate that the beam does not significantly affect the speed component of resistance. This is generally not considered to be the case since, in the majority of ice resistance predictor equations, the beam is included in the speed component of resistance with an index of at least unity.

Comparing the results of the Melville bow with the Original bow it may be anticipated that the change of resistance with L/B would be higher for the Original bow because of the high breaking component of resistance that would be expected with this ship. This is the case for the range of L/B tested.

4.5 Full Scale and Model Scale Comparison

Over the last five years the Original and modified 'M.V. ARCTIC' have undergone extensive full scale and model scale testing in a number of ice tanks. The objective of this section of the report is to assess and compare these test results with the midbody program of tests. The comparison is based on full scale predictions received from the various ice tanks and full scale data collected in the field.

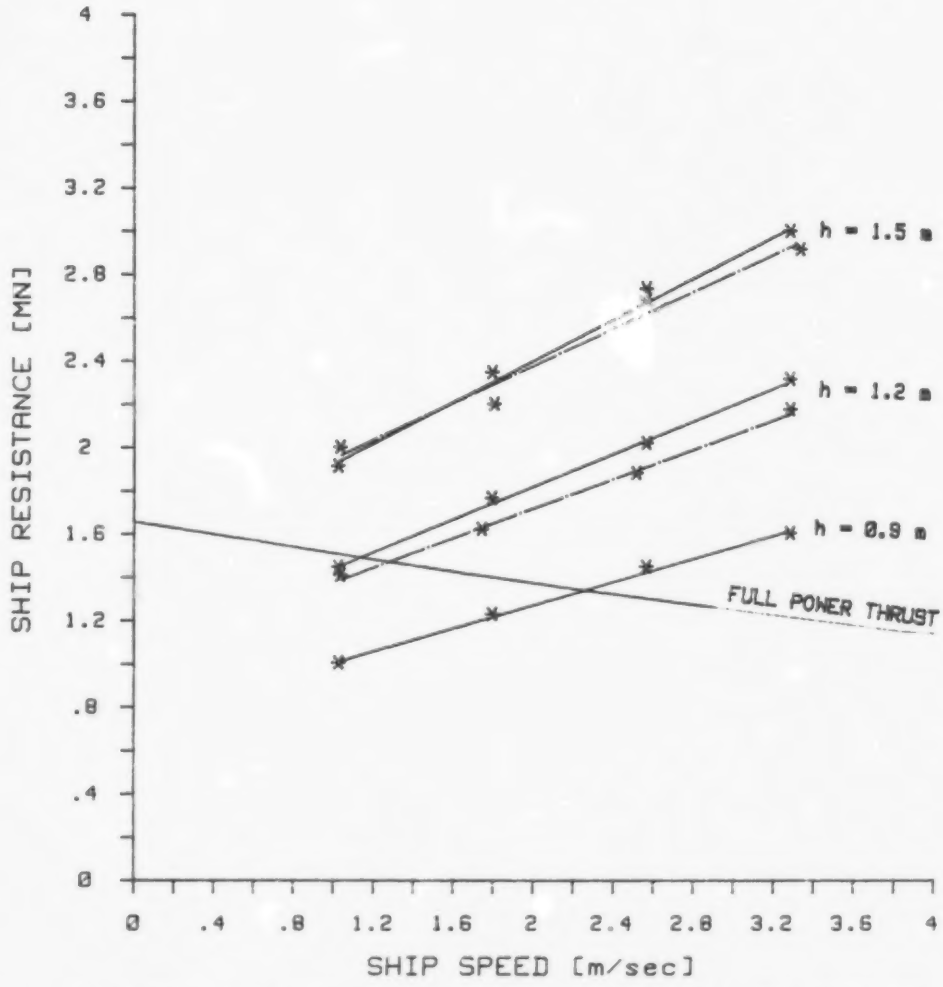
Figure 4.18 and 4.19 present the results from the midbody program for the ARCTIC with the Melville and Original bows respectively. Figure 4.18 also includes the results from the friction test program which can be seen to closely correspond to the midbody tests. It should be noted, however, that the midbody test ice sheet from which the full scale 1.2 m prediction line was generated was heavily corrected (Appendix C). As a result, the comparison between these two programs should be limited to the 1.5 m prediction line. The full power thrust line shown on the figures represent the total propeller and nozzle thrust from the ARCTIC's propulsion system at full power, reduced by the open water thrust deduction measured during overload open water tests with the model at NRC (Molyneux 1982).

Unfortunately there were not extensive full scale tests conducted on the Original bow, however it is believed that a reasonable estimate of the ship's original limiting ice thickness was about 0.9 to 1.0 m of level first year ice.

Figure 4.19 shows two performance prediction curves. The first is based on the data collected from this model test program with the model of

FIGURE 4.18

FULL SCALE RESISTANCE vs SPEED FOR THE MELVILLE BOW FROM THE MIDBODY AND FRICTION PROGRAMS



Midbody test program ; Ice sheet #1 #2 and #3
Friction test program ; Ice sheet #1 and #2
Data corrected to target strength and thickness
Target ice thickness = 0.9 1.2 and 1.5 m
Target ice strength = 500 kPa
Friction Coefficient = 0.06
Midbody Program = Solid line
Friction Program = Broken line

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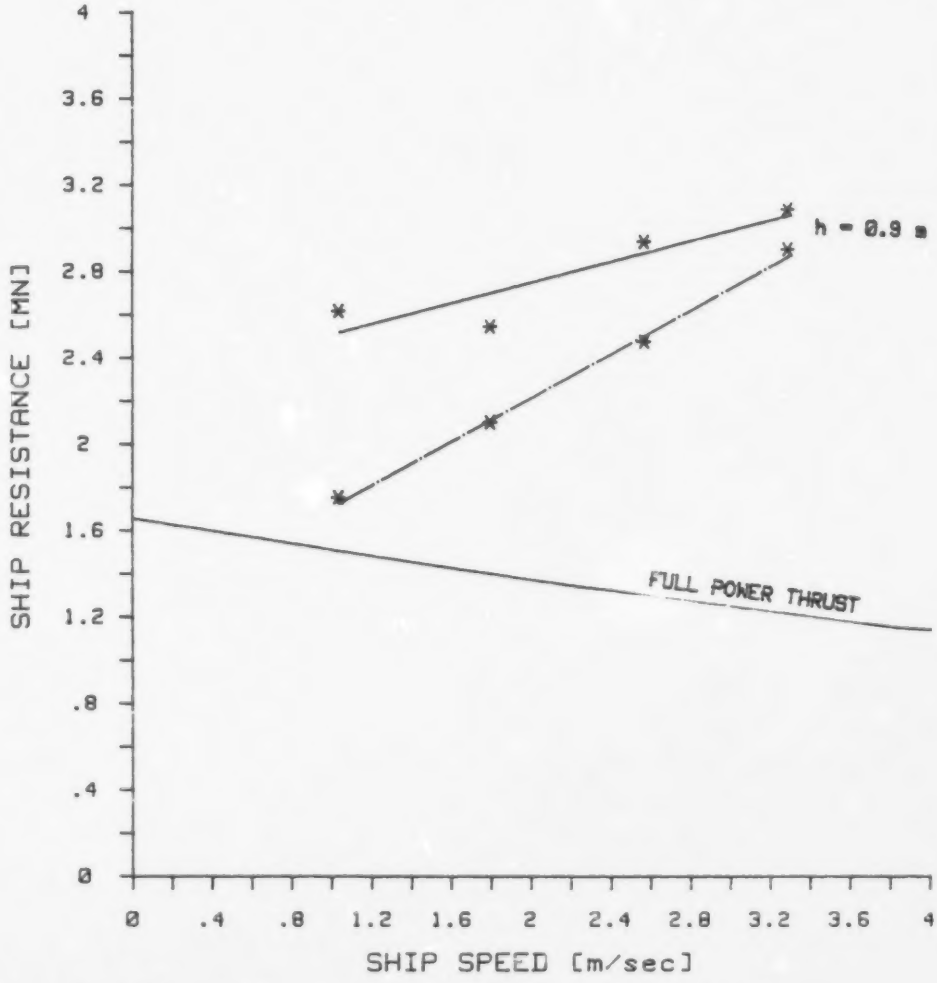
FIGURE 4.19

RESISTANCE vs SPEED FOR THE ORIGINAL ARCTIC BOW BASED ON TEST RESULTS AND AS ADJUSTED



Midbody test program ; Ice sheet #11
Data corrected to target strength and thickness
Target ice thickness = 0.9 m
Target ice strength = 500 kPa
Friction Coefficient = 0.06
As tested data = Solid line
Adjusted data = Broken line

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the existing ship. Like the results from the Melville bow, the model test prediction is lower than the full scale performance. The second performance prediction line shows the data deduced from the long and short ship models tests with the Original bow. Although, like the Melville bow form, this prediction line also under predicts the actual performance of the Original ARCTIC, the prediction is significantly closer to the full scale data and is believed to further justify the use of the interpolated resistance data for the Original hull form.

Figure 4.20 presents the accumulated data for the Melville bow. The full scale performance line is based on the full scale trials of the vessel conducted in 1986 {Dick 1986}. The line is generated from full scale data points measured from the speed in open water, 1.5 m level ice, 1.1 m level ice, and 0.8 m level ice. The data is represented by a curved line drawn through the data and found to closely represent the entire data set.

The results of this comparison clearly show how the performance prediction generated from the IMD test results is lower than both the full scale performance of the ship and the full scale performance predictions from the other ice tanks. The reason for this under prediction is not clear. For example, the full scale ship is capable of moving through a 1.2 m level ice field at about 5.8 knots. The prediction from the Hamburgische Schiffbau-Versuchsanstalt GmbH (HSVA) ice tank is about 4.8 knots, from Arctec Canada Ltd. (ACL) and the Wartsila Arctic Research Centre (WARC) about 3.2 knots, and from IMD about 2.2 knots.

It is interesting to note, however, that the limiting performance of prediction from each of the tanks appear to be the same and coincides quite well with the full scale performance. The correlation at the limiting thickness may be a coincidence of model scale, or that the tank predictions are more accurate at lower speeds.

The explanation of these differences are not known. However, there are a number of important considerations that may have an influence;

- The first test at ACL was conducted in 1982, since then six years of change and development of ice tank testing technology have occurred.

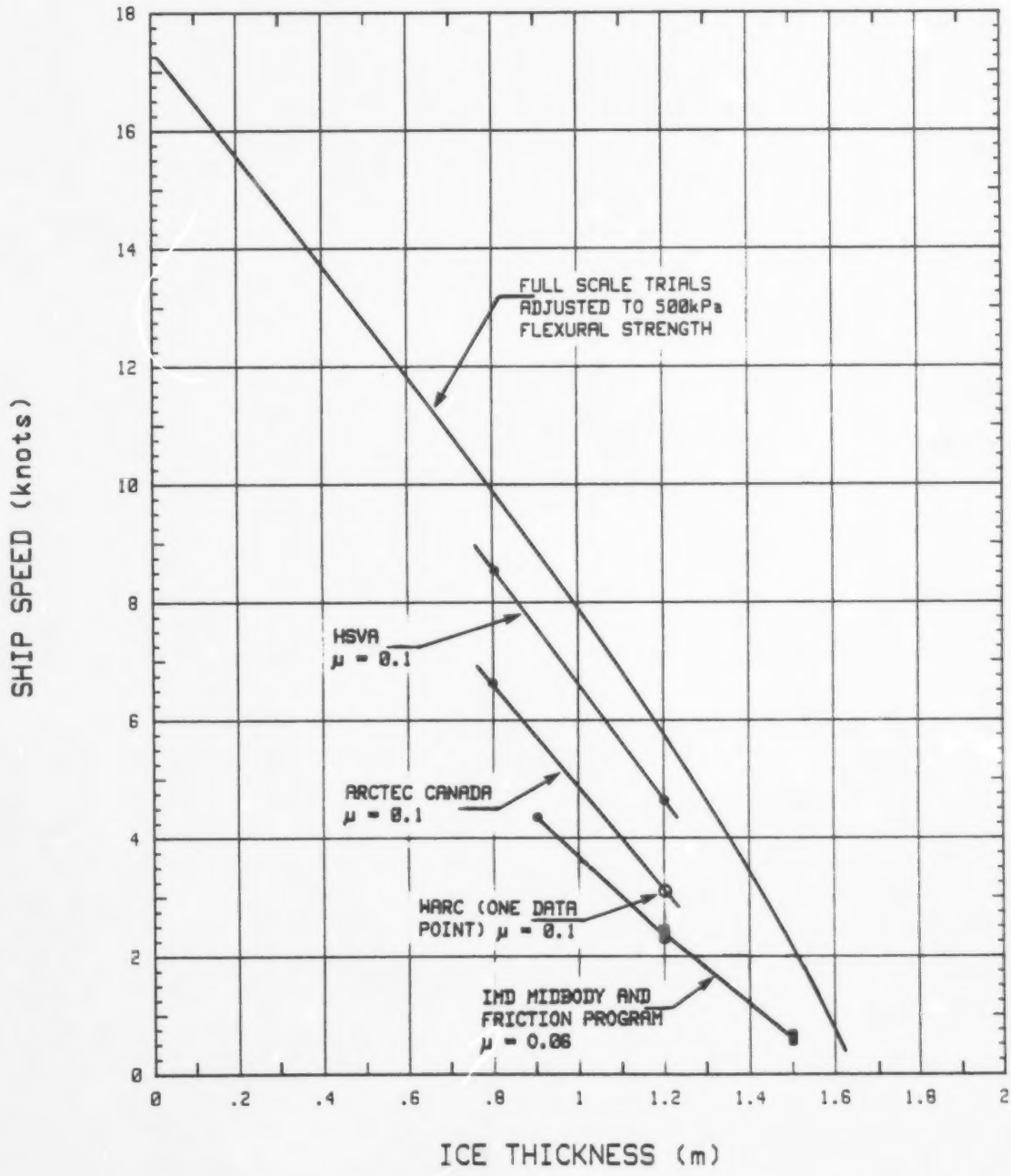
- The four different ice tanks used different ice. Carbamide (or Urea) ice was used at ACL and HSVA, Saline F.G. ice at WARC and the newly developed EG/AD ice at IMD.

- The four different ice tanks used different test procedures, this ranged from different seeding and tempering techniques to different types of resistance, or in the case of HSVA, self propulsion tests.

Not withstanding these considerations, there is clearly a significant difference between the performance predictions from each tank. This highlights a major concern and reinforces the argument for having model full scale correlation to support the model test results.

FIGURE 4.20

MV ARCTIC - SPEED VERSUS ICE THICKNESS
COMPARISON OF MODEL AND FULL SCALE RESULTS



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It should also be assumed that this model/full scale correlation will be different for each type of generic bow tested. For example, the correlation for a 'Melville' type bow will be different from a 'Spoon', 'White' or 'R-Class' bow. This is considered to be a reasonable assumption since the mechanical properties of the ice are different from full scale and therefore will have a different effect on each model tested since each generic form will break the ice differently.

Model testing in a simulated ice sheet is a relatively new technology and is constantly under review and change. The advances in understanding the technology have been made by test programs, such as the midbody program described in this report or the Friction Project, that address the fundamental relationships between model form and resistance and the effects of model ice mechanical properties.

The results of the model tests shown in Figure 4.20 must therefore be considered in context, recognizing that the final prediction of performance must be derived from model data, using some form of correlation analysis and full scale data from existing ships.

5. CONCLUSIONS

The model tests described in this report represent one of the first attempts to clearly define the influence of midbody length on the resistance of an icebreaker. As discussed in Sections 2, 3 and 4 there were a number of anomalies in the test program and, since there is very little existing data with which to compare results and validate trends, it was very difficult to determine, with any confidence, what these trends were.

Notwithstanding this problem, a significant level of effort was undertaken to generate data in which we could have confidence. To some extent this was successful but it should be clearly noted that in other areas, described above, the results generated from the ice test sheets are not considered by Melville to be representative of the actual relationships.

A total of 14 ice sheets were used, in conjunction with 14 different model configurations, to investigate the influence of friction, ice thickness and midbody length on resistance. Unfortunately, unavoidable problems caused by a number of different factors influenced the quality of several ice sheets. This was largely manifested in the low strength data associated with some of the data points and the range of strengths within any one sheet. Although ice strength was monitored as frequently as possible, the exact extent of strength fluctuations is not known, nor is the influence they may have had on the model resistance.

This introduces the compromise between taking more or less strength data. Fewer strength measurements would have resulted in less information on each ice sheet; more strength measurements which take more time, promote ice softening and deterioration.

Although the ice strength Indexer, which would have easily solved this particular problem, was used during each of the tests, the unit is still at an experimental stage and requires further calibration and repositioning in the ice tank. As a result, only limited confidence could be placed in the output from the Indexer, although it was used to assist in the selection of sample intervals and the analysis of the resistance data output. Ice strength and resistance trends were identified between the model and Indexer data, and the exercise proved the value of being able to monitor ice characteristics on a continuous basis down the ice tank.

In addition to low ice sheet strength, the results from the test program have also resulted in a number of anomalies in the data that appear to have been associated with otherwise normal ice sheets. These are, for example, the significantly higher resistance obtained from the original configuration of the ship compared to longer and shorter hulls. This anomaly is compounded when it is shown that an interpolation between the short and long model data to the original ship length results in a performance prediction considerably closer to the known full scale performance of the original ship.

In addition to recognising the perceived irregularities of the ice mechanical properties it is also important to review the results and question their overall credibility. The criterion for such a review are the simple laws of physics and the culmination of model ice testing experience gained over several years. Based on these criterion alone, some of the data generated by this program of work is questionable.

As with any physical model testing and particularly in a research area like model ice testing which is constantly under development, it should be expected that scenarios may arise giving non-consistent data. However, long and scientifically precise ice model programs can be conducted and the friction program, conducted by Melville Shipping Ltd. at IMD in 1987/88 and sponsored by TDC is a good example when ice sheets were generated in a consistent and repetitive fashion, over a period of several weeks.

The primary conclusions to this test program may be summarised as follows;

a) The influence of the midbody length on the resistance of icebreakers is dependent on the bow form, and model speed.

b) A thickness correction factor has been developed and shown to be useful for correcting ice thickness variations at model and full scale.

c) The ice strengths associated with a number of the ice sheets were considered to be too low for conventional test correction. As a result, the affected data points were analysed in more detail and adjusted for the parametric variation analysis.

d) In almost every case that a test was conducted in ice strengths lower than about 14 to 15 kPa, the resultant resistance was higher than adjacent data points associated with higher strengths. This phenomenon was observed in a number of ice sheets and may be associated with higher ice plasticity. The solution to this problem for the ice tank is to limit the lower strength of their tests. However, this result may also impact in a significant way on the correction of full scale data which is often collected in weaker ice and adjusted to winter ice conditions.

e) The ice strength Indexer was used during the test program for monitoring the ice sheet properties. Although the equipment is still undergoing trials, the results were very encouraging and demonstrated that ice sheet monitoring on a continuous basis proves very valuable. This was particularly the case when, as with this ice sheet program, there were large variations in the ice properties within one ice sheet.

f) The high friction coefficient test yielded a significantly higher speed dependency than would have been anticipated.

However, the presawn tests in the same ice sheet did not demonstrate a similar characteristic. This is possibly due to a different ice fracturing and ice/hull interaction due to the high friction coefficient. However, the high speed dependency only occurred during the tests with a high friction coefficient on the bow and midbody and not during the tests of the high friction bow and lower friction midbody. This is clearly an area of some importance and should be studied in more detail.

g) Results from models representing ships of different length but constant beam were compared. The results of the analysis indicate that an increase in length will result in an increase in resistance. The rate of change is speed dependent, increasing with high speeds. The increase is also bow dependent, being higher for the Original bow form than the Melville bow.

h) Manipulating the scale of each model to yield a prototype ship with a displacement 20 percent higher and 20 percent lower than the original ship indicated that a 20 percent variation in displacement results in about a 4 to 7 percent variation in resistance.

i) Manipulating each model with a scale that would result in a prototype ship of the same displacement indicated that higher L/B ratio ships tend to have lower resistances. It is not considered that any real maximum or minimum values were found in this analysis.

6. RECOMMENDATIONS

As with any research based work, the development of new procedures and understanding is always associated with additional questions and the identification of areas that require additional work. The model test study and associated analysis described in this report has resulted in a number of recommendations. These may be summarized as follows;

a) The need to evaluate and monitor ice strength has been highlighted as a major concern to the model ice experimenter. Often due to low staffing levels, the required number of personnel are not always available for thorough ice sheet definition. This program of tests illustrates both the potential for ice strength variation and the lack of standard procedures for correcting data that falls outside standard test windows. For the last few years Melville have been developing, in association with IMD and TDC, an ice strength Indexer that can be used to monitor and calibrate an ice sheet along its entire length. The development and interpretation of the Indexer output should form a high priority for all those involved in the operation, use and interpretation of model scale tests in ice.

b) A number of the ice sheets, some due to strength inconsistencies and some inexplicably, yielded unusual resistance data. To validate the results of this program it is recommended that additional model tests are conducted. These are:

   i) High friction coefficient on the Melville bow form. This will investigate the high speed dependency observed during ice sheet #4. The tests should include underwater photography, specifically arranged to monitor ice cusping patterns.

   ii) Thin ice resistance for the Melville bow. The results from the test program to date indicated a low ice thickness dependency resulting in a significant under-prediction of performance. This should be investigated through thinner ice sheet tests of, for example, 10, 20 and 30 mm corresponding to 0.3, 0.6 and 0.9 m full scale.

   iii) The limiting full scale performance of the ARCTIC is about 1.5 to 1.6 m of level first year ice. As a result, continuous level ice performance tests do not exist in thicker ice. However, full scale data from long rams does exist and from these it is possible, from an analysis of the de-acceleration during the ram, to determine resistance. Since full scale ramming data exists for level ice thicknesses up to 1.85 m, an additional model test should be conducted at this higher ice thickness from which a comparison may be made to the full scale data.

iv) The Original bow should be re-tested with the ships original length. This would repeat ice test number 11 in which unusually high resistance values were recorded. The results will be used with the tested length combinations to yield a more consistent length trend.

c) The phenomenon of lower ice strengths associated with higher resistances introduces an extremely important anomaly to both full scale and model scale data interpretation. Additional ice tests should be conducted with very low ice strengths, for example, 5 to 10 kPa to investigate this in more detail. The monitoring of such low ice strength mechanical properties would probably have to be done with the Indexer.

d) The ice sheet properties at the IMD ice tank are carefully monitored and recorded for every ice sheet. The extent of analysis undertaken on this data has been done largely on an opportunity basis with little or no formal presentation of data or results. The IMD has now completed over 200 ice sheets. It is considered that a major benefit would accrue from a detailed review of this data. This would include a description of the ice formation process and the parameters that influence the ice growth, together with a statistical analysis of the ice mechanical properties and the influence of each variable on the resultant ice properties.

BIBLIOGRAPHY

Baker 1986: Baker, D.N., et al, "A Strength Indexer for Model Ice", ATTC 1986.

Dick 1986: Dick, R.A., "MV ARCTIC Ship Performance Testing Spring 1986", Melville Shipping Ltd., July 1986.

Forland 1985: Forland, K.A., "Kinetic Friction Coefficient of Ice.", CRREL, 1985.

IMD 1987: Spencer, D., "Ice Model Tests On CCGS LOUIS S. ST. LAURENT, Phase I - Models M395A, M395B, M395C", Institute for Marine Dynamics, March 1987.

ITTC 1987: Ice Tank Towing Conference, Report of the "Performance in Ice-Covered Waters Committee".

Jones 1987: Jones, S.J. et al. "Ice Tank Model Test Methods at IMD", IMD Report LM-AVR, May 1987.

Melville 1984: Melville Shipping Ltd., "Redesign of the M.V. ARCTIC Bow - Design and Model Testing", TP5456E, Transportation Development Centre, November 1984.

Melville 1985: Melville Shipping Ltd., "Redesign of the M.V. ARCTIC Bow - Additional Model Tests at HSVA and WARC", TP5812E, Transportation Devleopment Centre, May 1985.

Melville 1987: Melville Shipping Ltd., "Ice/Hull Friction Coefficient Study", TP 8915E, Transportation Development Centre, October 1987.

Molyneux 1982: Molyneux, W.D., "MV ARCTIC and Two Alternative Bow Designs Results of Resistance, Propulsion and Overload Experiments with Model Hulls 326, 326B and 326C and Model Propeller 68", AVMRI, May 1983.

Timco 1985: Timco, EG/AD/S: "A New Type of Model Ice For Refrigerated Towing Tanks", Cold Regions Science and Technology, October 1985.

APPENDIX A

TEST PLAN

P87-21

T8200-7-7529

EXAMINATION OF THE INFLUENCE OF PARALLEL MIDBODY ON THE RESISTANCE OF ICEBREAKING SHIPS

- TEST PLAN -

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January 1988

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1. TEST PLAN OBJECTIVES

This test program is designed to investigate the influence of parallel midbody length on ship's resistance when navigating in ice.

The test program utilises an existing segmented model of the OBO carrier ARCTIC, which has been altered to obtain four different lengths of parallel midbody. Since there is believed to be a difference in the midbody influence as a function of bow shape and friction coefficient, the existing model of the ARCTIC will be augmented with the original bow, fitted to the ship prior to the Melville bow construction in 1986, and will include 3 different friction coeficients.

The tests will be completed at IMD, under the direction of Melville Shipping Ltd, in January and February of 1988.

The primary objective of this work is to assess the influence on resistance in ice of the parallel midbody length of icebreaking ships. However, there are several more detailed objectives which the project will attempt to achieve:

a) Quantify the percentage of total ship resistance in ice, that is contributed by the parallel midbody.

b) Determine how this percentage varies as the parallel length is increased or decreased.

c) Determine the influence of ship speed on the parallel midbody variation.

d) Determine the influence of bow shape, on the parallel midbody variation.

e) Determine the influence of bow friction coefficient on the parallel midbody variation.

f) Establish how the full scale performance of a ship in ice may be adjusted to compensate for a variation in parallel midbody length.

g) Determine the thickness dependence of resistance with the Melville bow at IMD.

h) Determine the influence on resistance of hull proportions at a constant displacement.

2. MODEL TEST PROGRAM

2.1 Overview

The model is a 1:30 scale reproduction of the ARCTIC, an Arctic Class, 28,000 tonne DWT OBO carrier. The model tests consisted of 11 towed resistance tests in model EG/AD ice representative of 1.0 m, 570 kPa full scale ice. Additional tests will also be conducted in ice equivalent to 1.2 m and 1.5 m thick, to investigate the effect of ice thickness and as a comparison with results from previous model tests. These ice thicknesses and strengths correspond to 30 mm, 40 mm and 50 mm, 19 kPa model ice. The ice strength is nominally higher than would have been preferred but was selected to ensure consistent model ice strength, which is difficult to obtain with weaker ice.

The measured properties of the ice will be achieved with an accuracy defined by;

Ice thickness; +/- 5% of target thickness.

Ice Flexural Strength; +/- 10% of target strength.

If, during a test, the ice strength varies by more than these criteria then the tests will be subject to a special analysis and may have to be repeated.

The models of the ARCTIC are constructed in segments to a scale of 1:30. For the model tests which have previously been completed, one parallel midbody section was bolted between the stern and bow section. This represented the actual length of the ship. However, with minor modifications to the model, the middle segment may be removed and the bow and stern bolted together, thereby eliminating much of the parallel midbody of the ship. Alternately, additional midbody segments may be added to lengthen the model.

The segments for this test program have been selected to yield the most uniformly distribution range of model lengths whilst still being compatible with the necessary testing instrumentation.

The shortest model, Ship 1, is represented by attaching the bow section to the stern section. Unfortunately the forward end of the stern section does not represent the full midship section and small fairing pieces will be used to ensure smooth and continuous hull lines.

Ship 2 is represented by fitting a half midbody length between the existing bow and stern. The longer ship is represented by using the full length midbody, plus an addition 2/3 midbody length.

The combinations of segments that have been selected are shown in Table 2.1. Table 2.1 also shows the approximate dimensions of the full scale ship represented by each model. There are two base ships, one with the original bow and the second with the Melville bow, and three other variations, two shorter and one longer.

TABLE 2.1
MODEL CONFIGURATIONS

Parameter	Base Ship Old Bow	Base Ship Melville Bow	----- Melville Bow ---- Shorter Ship 1	Shorter Ship 2	Longer Ship	-----Old Bow ----- Shorter Ship 1	Longer Ship
Length BP (m)	201.00	210.00	138.00	176.00	262.00	128.00	253.00
Breadth (m)	22.87	22.87	22.87	22.87	22.87	22.87	22.87
Draft (m)	11.00	11.00	11.00	11.00	11.00	11.00	11.00
L/B	8.98	9.18	6.04	7.69	11.46	5.60	11.06
% of Base Ship	100%	100%	68%	83.8%	124.8%	63.6%	125.9%

2.2 Test Schedule

The overall test schedule is shown in Table 2.2. A total of 14 ice sheets will be tested during January and February 1988. The first test will be conducted during the week of the 18th of January.

TABLE 2.2

PARALLEL MIDBODY PROJECT - PLUS EXTENSION
MODEL TEST PROGRAM MATRIX

MODEL PART FRICTION	MELVILLE BOW 0.4	0.06	0.004	ORIGINAL BOW 0.4	0.06	0.004	SHORT MIDBODY 0.4	.06	WHOLE MIDBODY 0.4	0.06	STERN 0.1	COMMENTS
Ice Sheet #1		■								■	■	h = 50 mm
Ice Sheet #2		■								■	■	h = 40 mm
Ice Sheet #3		■								■	■	h = 30 mm
Ice Sheet #4	■								■		■	h = 50 mm
Ice Sheet #5	■										■	h = 30 mm
Ice Sheet #6				■							■	h = 30 mm
Ice Sheet #7		■									■	h = 30 mm
Ice Sheet #8			■								■	h = 30 mm
Ice Sheet #9						■					■	h = 30 mm
Ice Sheet #10					■						■	h = 30 mm
Ice Sheet #11					■					■	■	h = 30 mm
Ice Sheet #12					■			■		■	■	h = 30 mm
Ice Sheet #13		■						■			■	h = 30 mm
Ice Sheet #14		■						■			■	h = 30 mm

2.3 Model Preparation

The basic models used for this test program are 1:30 scale reproductions of the Arctic Class 2 O.B.O. M.V. ARCTIC, before and after the installation of the Melville Bow.

The model draught for all the tests will be representative of 11 m full scale, 36.7 cm model scale. The longitudinal centre of gravity will be adjusted to yield a level trim and the vertical centre of gravity will

be adjusted to yield a metacentric height of about 1.5 m full scale or 0.05 m model scale.

The Metacentric height will be calculated from a standard model inclining experiment, and the radii of gyration will be estimated using a standard relationship:

$$T = 2\pi k \sqrt{\frac{(1+a)}{g \times GM}}$$

T = Period

k = radius of Gyration

GM = Metacentric height

a = 0.2; for roll

= 0.9; for pitch

The program will adopt standard resistance procedures with the model restrained in surge, sway, yaw and free to move in pitch, roll and heave. Instrumentation will be used to record the latter three degrees of freedom.

The model resistance will be recorded using the IMD towing post. The towing post load cell is calibrated prior to every test using deadweights, supported by a two pulley calibration jig, and a cord attached to the stern of the model.

2.4 Test Procedures

The IMD standard test procedures will be adopted in this test program with a number of minor additions. These are described in the following text.

a) Test Location:

The location of the test area within each ice sheet will be defined prior to the test. The area shall be such that the model motions and speed are stable. The test area shall be at least the length of the model and will be preceeded by a "settling in period" which is determined by scale. The model shall be completely surrounded by ice prior to the test. It is anticipated that there will be at least three test locations per ice sheet.

b) Flexural Strength:

The flexural strength will be measured using a floating cantilever beam cut from the ice sheet. The cantilever beam will be loaded manually with calibrated spring gauges, to failure, and the maximum force during the failure will be recorded. The beams will have the overall dimensions, length, width and thickness of 5:2:1. Three beams will be tested downwards and one upwards, in four positions within each test location. Each set of the beams will be tested at about 800 mm from the model centreline. The beams are to be cut

and tested immediatly prior to the model test time. The dimensions of the beams will be measured immediatly after the ice thickness profile following the model test. Values of flexural strength will be calculated based on an extrapolation of the tempering curve from the cantilever test time to the model test time. The reported value of flexural strength will be the average of the 12 beams tested in that particular test location.

c) Thickness:

The ice thickness will be measured, using callipers, immediatly after the model test, prior to measuring the cantilever beam dimensions. The thickness will be recorded every two meters down the length of the ice tank. The measured ice samples will be taken from the north and south side of the broken track left by the model.

d) Compressive Strength:

The compressive strength will be measured at four positions in each test location using a lever and fulcrum jig designed by IMD. The apparatus measures uniaxial compressive strength calculated from the force necessary to crush an ice sample in the horizontal plane. The reported value for the location will be the mean of the four values.

e) Elastic Modulus:

The elastic modulus (characteristic length) will be measured at least three times during the ice sheet tempering with the final measurement taken within 60 minutes of the test time. The elastic modulus is calculated using an ice sheet diplacement under a series of known loads and the relationships developed by Wyman (Canadian Journal of Research 1950). The reported value will be the value extrapolated from all the tests.

f) Ice Density:

The ice density will be recorded within 60 minutes of test time, by deducing the submerging force of a known volume of ice sample in a container of tank melt.

The submergine force is measured by noting the difference in total weight of a container before and after the ice piece is submerged in a plunger.

g) Fracture Toughness:

The ice sheet fracture toughness will be recorded at least three times during the tempering process by taking four samples on the north and south side of the tank. The fracture toughness will be measured using the procedure described by Atkins (Journal of Ship Research, 1975). An ice sample will be cut from the ice sheet and the force necessary to propogate an initial crack of known length and configuration in the vertical place is measured. The reported value will be the extrapolated value at test time.

h) Ice Friction:

Ice friction will be measured by taking a 0.14 m square sample from each test location and drawing a board under it at 10 cm/sec. Every attempt will be made to ensure that the surface of the board is prepared with an identical surface to the model. Normal pressures generated should be at least 1, 2.5, 5 and 10 Kpa, with higher normal pressures if possible. The curves of ice friction coefficient vs. normal pressure will be reported. Additional sample speeds will be attempted if possible.

i) Presawn Tests:

Pre-sawn tests will be conducted on the north or south side of the tank at model speeds corresponding to the speeds in level ice.

j) Slow Speed Test

At the end of each test run, the model will be tested at very slow creeping speed for appoximately 1/2 ship length.

3. ANALYSIS PROCEDURE

3.1 Overview

Although it is anticipated that the ice thicknesses and strengths will be achieved with a high level of accuracy it will be necessary to make corrections to the measured resistance for minor variations in the ice mechanical properties. To more clearly define and describe the data analysis it will be subdivided into a number of subsections which are;

a) Data overview; A review of the data collected, its overall consistency and the level of confidence that can be placed in the results.

b) Data correction; The normalisation of the data to a common ice thickness and strength for analysis

c) Data analysis; The analysis of resistance data, at model scale, as a function of friction coefficient, model length and bow form. The conversion of model scale to full scale for comparisons with the available full scale data and other tank results.

3.2 Data Presentation and Analysis

3.2.1 Data Overview

The data overview will consist of a general review of the model data in terms of its consistency with itself (regular curves of resistance vs speed) and with other model tests of the ARCTIC conducted by Melville at IMD over the last few years. This analysis will include an assessment of the measured ice properties to check that they comply with the defined limits of ice strength permissable during the tests.

3.2.2 Data Correction

The model tests will all be conducted with target ice thicknesses and strengths, however, as with any physical testing, the target values may not always be obtained. As a result some minor adjustments or nomalisations may be necessary to ensure that when the data is analysed for variations in friction coefficient, length and bow form, the comparison is independent of ice thickness and strength.

There are a number of methods that may be used to normalise the data and these may be summarised as;

1. Thickness and ice strength corrected as a function of a variable group in the form.

$$R_c = R_m * \{(h_t^a \times \sigma_t^b) / (h_m^a \times \sigma_m^b)\}$$

R_m = Measured Resistance
R_c = Corrected Resistance
h_m = Measured thickness
h_t = Target thickness
σ_m = Measured strength
σ_t = Target strength
a, b = Empirical indices, normally between zero and two.

2. Based on tests with the same model in different ice thicknesses, a relative extrapolation or interpolation to the target thickness, based on a constant ratio of; rate of change of resistance with ice thickness, over measured resistance at a specific speed.

3. Based on presawn, or zero strength ice tests, a relative extrapolation or interpolation to the target ice strength based on a constant ratio of; rate of change of resistance with ice strength, over measured resistance at a specific speed.

Any one, or a combination of these correction methods may be used and are discussed in the following text.

The correction to target ice thickness and strength using the variable group of thickness and strength is based on the assumption that the resistance conforms in a consistent way to these variables, raised to a selected index, independant of bow form. Work associated with this type of analysis has shown that this is not always the case, and often different indices are necessary depending on the bow form.

An alternative method for correcting the resistance data is to use tests of the model in a different ice thickness for the thickness correction and the results of the presawn tests for the strength correction. The correction to resistance for variations in thickness is calculated by assuming a linear relationship between the resistance and thickness for a specific speed. The resistance at the target ice thickness is simply interpolated between the two values of resistance at different ice thicknesses. When data exists this is done independently at each speed, if data at all the speeds does not exist then a constant relative rate of change of resistance with ice thickness is calculated for the closest speed.

The correction to resistance for variations in strength is calculated from the zero strength or presawn ice sheets. The resistance of the model in the presawn test is assumed to correspond to zero flexural strength. Using this value, and the measured value during the normal level ice test at the same speed, the resistance at the target ice strength is calculated by interpolation, or extrapolation. In the event that an identical speed was not run in the presawn condition, then the relative change in resistance as a function of strength is calculated from the closest speed and used in lieu.

Based on an assessment of these, and alternative correction procedures, the data will be normalised to target ice properties.

3.2.3 Data Analysis

The results from the model tests will allow relationships to be developed between resistance, length, bow shape, friction coefficient and ship speed. These relationships may be summarised as;

i) Resistance versus length will be obtained over the range of lengths and for each bow shape and plotted as a function of speed. These relationships will be developed for a friction coefficient of nominally 0.06. The plots will illustrate the influence of length on resistance at various ship speeds. The influence of bow shape can be obtained for the same lengths, speeds and friction coefficient.

ii) Resistance versus speed will be plotted at three friction coefficients for the short ships and integrated into the results from (i) to obtain the effect on length variation. These plots will illustrate the influence of speed and friction coefficient on length variation for each bow.

iii) For each model combination of length and bow shape the scaling factor will be changed to vary the displacement by +/- 20% and plotted as resistance vs displacement. To accomplish this with some confidence it will be necessary to determine the influence on resistance of variations in ice thickness and strength.

iv) The scaling factor for each of the models which are either shorter or longer than the ARCTIC will be changed to create the same displacement as the ARCTIC. In each case the full scale resistance will be assessed for those models in 1.0 m thick, 570 kPa flexural strength ice. This will allow a comparison to be made between ships of the same displacement but for different main dimensions. The research conducted for item (iii) on resistance variation with strength and thickness will be used when assessing the modified ships.

The results will be presented in absolute and percentage terms. Tabular and graphical forms of presentation are to be adopted.

4. RESULTS

The results of the test program will be used to develop a number of relationships. These are illustrated in a schematic form in Figure 4.1 and may be summarised as follows:

i) Resistance as a function of ship speed for each length, bow and friction coefficient, Figure 4.1 (a) and (b).

ii) Resistance as a function of length, independent of displacement at one friction coefficient and a range of speeds. Figure 4.1 (c).

iii) Resistance as a function of the friction coefficient for each short ship in 30 mm ice and for the base ship in 50 mm ice. Figure 4.1 (d) and (e).

iv) Resistance as a function of diplacement (+/- 20%) for each model configuration at a range of speeds. Figure 4.1 (f).

v) Resistance as a function of main dimensions (eg. length) at constanct displacement. Figure 4.1 (g).

vi) Ship speed as a function of ice thickness. Figure 4.1 (h).

FIGURE 4.1

LENGTH VARIATION PROGRAM

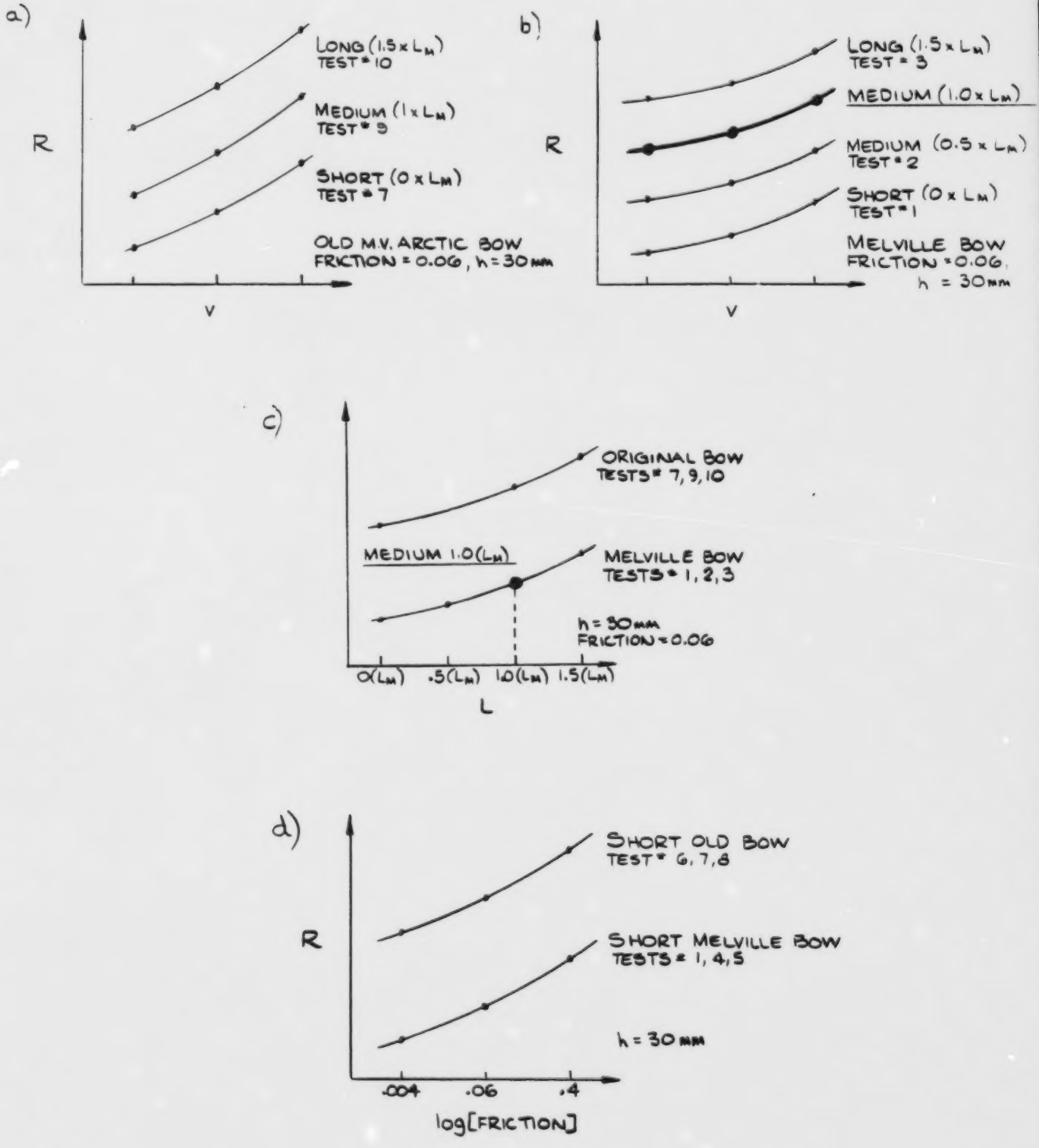
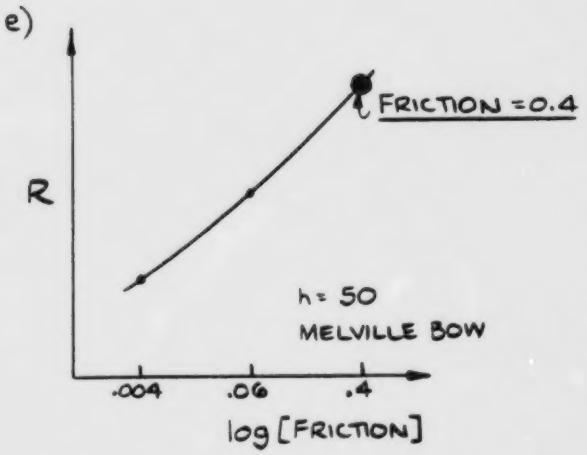
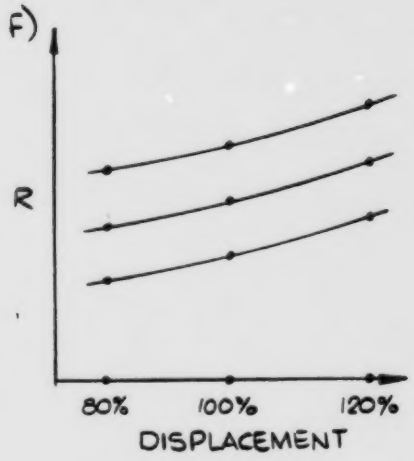
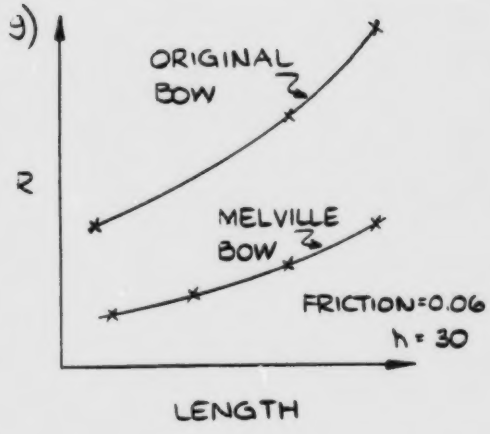
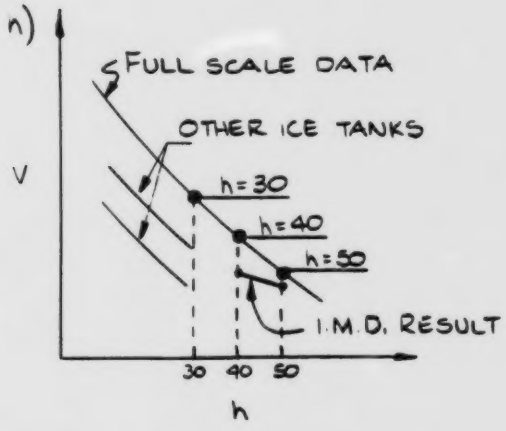


FIGURE 4.1 (cont)









APPENDIX B

PARALLEL MIDBODY LENGTH EFFECTS ON SHIP MODEL RESISTANCE IN LEVEL ICE

National Research Council Canada
Institute for Marine Dynamics

Conseil national de recherches Canada
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PARALLEL MIDBODY LENGTH EFFECTS ON SHIP MODEL RESISTANCE IN LEVEL ICE

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J.B. Snellen

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SUMMARY
This report describes a series of model tests carried out in the ice tank at IMD, between January 19 and February 12, 1988, for Melville Shipping Limited and sponsored by the Transportation Development Centre. The purpose of the tests was to study the effect of changing the length of a ship's parallel midbody section on the resistance measured in level ice.

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PARALLEL MIDBODY LENGTH EFFECTS ON SHIP MODEL RESISTANCE IN LEVEL ICE

1.0 INTRODUCTION

This report describes a series of model tests carried out in the ice tank at IMD, between January 19 and February 12, 1988, for Melville Shipping Limited and sponsored by the Transportation Development Centre. The purpose of the tests was to study the effect of changing the length of a ship's parallel midbody section on the resistance measured in level ice. Additional elements in the test program had the purpose of further examining some of the features of previous test programs involving models of the M.V. Arctic. The effect of a rough midbody and the effect of a variation in roughness on the comparison between two bow forms, were also studied.

1.1 Literature Review

Effects of parallel midbody length on open water resistance have been studied in early naval architecture (Ref. 1), and are summarized in standard references (Ref. 2). In ice the influence on resistance of a parallel midbody was identified by Kitazawa and Ettema (Ref. 3), who report that the "Aft resistance is mainly due to the friction between the ice rubble and the hull's long parallel middlebody.

...this resistance component appears not to be velocity-independent and increases with model speed. The increasing frictional resistance between the model hull and the ice rubble is largely attributed to the increase in tightness between them, due to the narrowing track width with model speed ". The length of the parallel midbody was not varied in the aforementioned study.

Length variation was addressed in a study of the characteristics of icebreaker hulls but no significant effect was noted (Ref. 4). In a study of great lakes bulk carriers in ice (Ref. 5), three different model lengths were employed. The data from this study was presented in graphical form and is further discussed in part 13 of the conclusions section.

A recently translated Japanese study (Ref. 6) also employed three model lengths. The results indicate a slight increase of resistance with length. Graphs from this study are also discussed in part 13 of the conclusions section.

2.0 MODEL DESCRIPTION

The tests were carried out with a 1:30 scale model of the M.V.Arctic. Model sections constructed for the 1986/87 friction test program (Ref. 6) were used in addition to model sections constructed specifically for this project by a local contractor, B. Mulrooney & Associates. A total of eleven model pieces were employed. Figure 1 presents an overview of the model sections.

For the friction test program, a model of the M.V.Arctic with the new bow installed in 1986 was used. This model consisted of three sections, dividing the model at stations 2.29 m and 4.81 m forward of the aft perpendicular. Of the model pieces from that program, three identical bow sections of different friction coefficient, two identical middle sections (one rough and one medium finish) and one stern section were used in the present test program. The bow and midbody sections were made of molded fiberglass and the stern section was made of wood laminations.

The additional model sections built for this project included three bow sections of the original bow of the M.V.Arctic. These sections were made of fiberglass from a mold of the original bow model that was tested in 1983 (Ref. 7). They were finished with three friction coefficients corresponding to those of the three new bows (see Table 1 for the friction coefficients of all the model parts).

The middle section of the model, described in the preceding paragraph, is parallel-sided except for a slight tapering near the stern. The length of this middle section was varied during the present test program by inserting midbody sections of various lengths that were built specifically for this project. To obtain a wide range of length to beam ratios (L/B) it was decided to test the model without any midbody section as the shortest ship. This presented some problems, as the bow does not have a taper. Bilge pads were made and bolted onto the stern to give a fair fit to a bow when testing the short models. Next a midbody section, complete with taper, was made to a length of one half the full midbody using the fiberglass and mold technique. When inserted between bow and stern sections this made a model that was significantly shorter than the normal ship. Then the full midbody ship, which had been tested in previous programs, was retested during this project. Finally, the longest ship was created by bolting together a full midbody with an additional section of two thirds midbody length. This two thirds midbody was the longest parallel-sided section that could easily be made from the existing midbody mold using the fibreglassing technique.

3.0 MODEL PREPARATION

Prior to assembly, thin strips of plasticene were placed between model sections to prevent leakage of water through the bolt holes. The sections were then bolted together rigidly. The plasticene allowed a close fit, with spacing between sections generally less than 1 mm. The model was fitted with a bare hub, cone, duct and rudder.

The model was ballasted to the waterline and the ballast was adjusted to provide the target GM and model motions. A metacentric height (GM) of 0.050 m (1.5 m full scale) was selected based on information provided by Melville Shipping. The friction test program used a GM of 0.053 m, and a pitch period of 1.48 s and a roll period of 2.55 s for the model with a full midbody. These pitch and roll periods were used for the full length model in the present test program (see Table 2).

In addition to the natural pitch and roll periods, the pitch and roll motions when the model was subjected to forcing by the ice were taken into account. It was expected that as the shorter models approached the form (L/B ratio) of a "classical" icebreaker, as opposed to an icebreaking cargo vessel hull form, that the pitch motion would increase. An effort was made to keep the forced motion in pitch the same as the full-length model, in order to maintain the same icebreaking geometry in the zone where the ice interacts with the bow. This required longer natural periods than would be expected for short models, in fact the periods required were longer than those of the full midbody model (see Table 2). Using this approach, the length would be the only variable.

The model was attached to the large tow post on the ice tank carriage using a load cell gimbal that measured the tow force. This gimbal was mounted on a 1/2" aluminum base plate that bolted to each model midsection, thus allowing for easy model changes. The gimbal restrained the model in surge and sway, but allowed free movement in heave, pitch and roll. Yaw was restrained forward of the tow post, on the roll axis, using a 'grasshopper' attachment.

The gimbal locations were as follows:

(i) For short ships (bow and stern together) the models were towed from the stern section and the gimbal was mounted on a tapered 3" plywood base because the aluminum plate was too large for the stern.

(ii) The 1/2 midbody model was towed from the center using the same plywood base.

(iii) The full midbody models were towed from the center of the model.

(iv) The 1 2/3 midbody model was towed from the center of the full midbody, using the aluminum plate in its standard position. In effect this put the gimbal a 1/3 midbody distance behind the true center of the model. (Thought was given to towing this model from the true center, but the modifications required, at the expense of model rigidity, were considered prohibitive).

4.0 TEST PROCEDURES

The schedule of tests as outlined in the test plan was modified to accommodate a delay in model preparation. The actual sequence of tests is outlined in table 3.

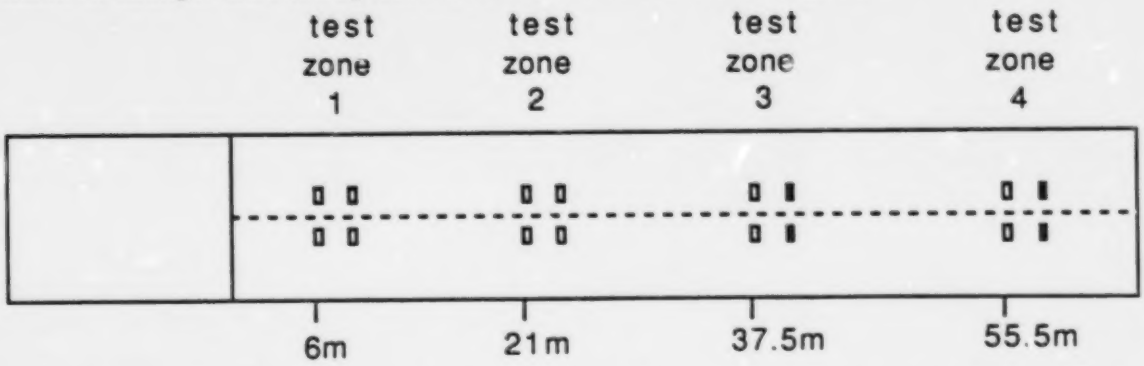
Target conditions for strength and thickness were specified by Melville Shipping in the test plan. A target strength of 19 kPa was used throughout the test program. Three target thicknesses, 50, 40 and 30 mm were used, see table 3. The ice tank tests were run as close to target conditions of thickness and strength as normal ice monitoring allowed.

4.1 Monitoring of Model Ice

The strength of the model ice decreases with time. This process, referred to as tempering, results from inclusions of ethelene glycol solution in the ice that grow and weaken it's structure. The process is readily predictable based on IMD's experience with EGAD ice, however, to monitor the ice strength on a detailed level, ice strength measurements are made on a routine basis. These measurements consist of eight downward and two upward breaking cantilever beams, from the quarter point locations halfway along the length of the tank. Average strength is calculated from the downward breaking beams. This measurement is used to determine the time for testing at the target strength. Table 4 lists the strengths at test time for this program.

4.2 Characterizing of Model Ice

To determine the strength characteristics of the model ice sheet as near as possible to the model test time, intensive strength measurements were done prior to the model test. The pattern of strength tests throughout the tank is illustrated in the diagram.



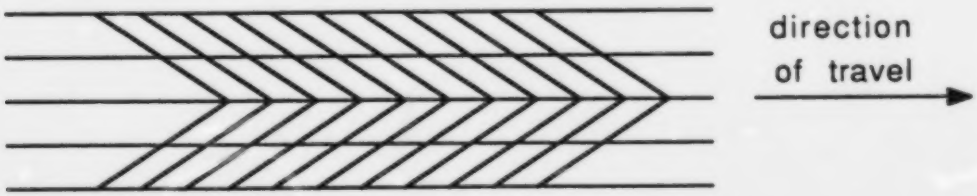
These strength measurements were corrected to strength at test time using a curve fitted to the data of strength versus time for all previous ice sheets in that thickness category. The test time strength measurements from each of the test zones were then used to correct the resistance measurements for variation in strength between zones (see section on data analysis).

4.3 Model Tests

Resistance was measured at five different speeds in level unbroken ice along the center of the ice tank. Then the test frame and model were moved to the 'quarter point' and resistance was measured in pre-sawn ice. The same set of speeds was used in each test: 0.189, 0.329, 0.470, 0.600 and 0.020 m/s. In addition the yaw load on the model was measured as were the model motions of port, starboard and center displacement for calculation of heave, pitch and roll.

The pre-sawn test involved ice that was cut into pieces using handsaws. The cut pieces were similar to those created by the bow`s breaking action. The pre-sawn pattern was cut as follows; first, five lengthwise cuts were made along the tank. Next, angled cuts were made across the tank, connecting the lengthwise cuts as shown in the diagram. The angle for the cross cuts was 'copied' from the breaking pattern of the model bow where it stopped at the end of the level ice run. Two slats of wood, clamped at the angle of the breaking pattern, acted as a guide during the cutting.

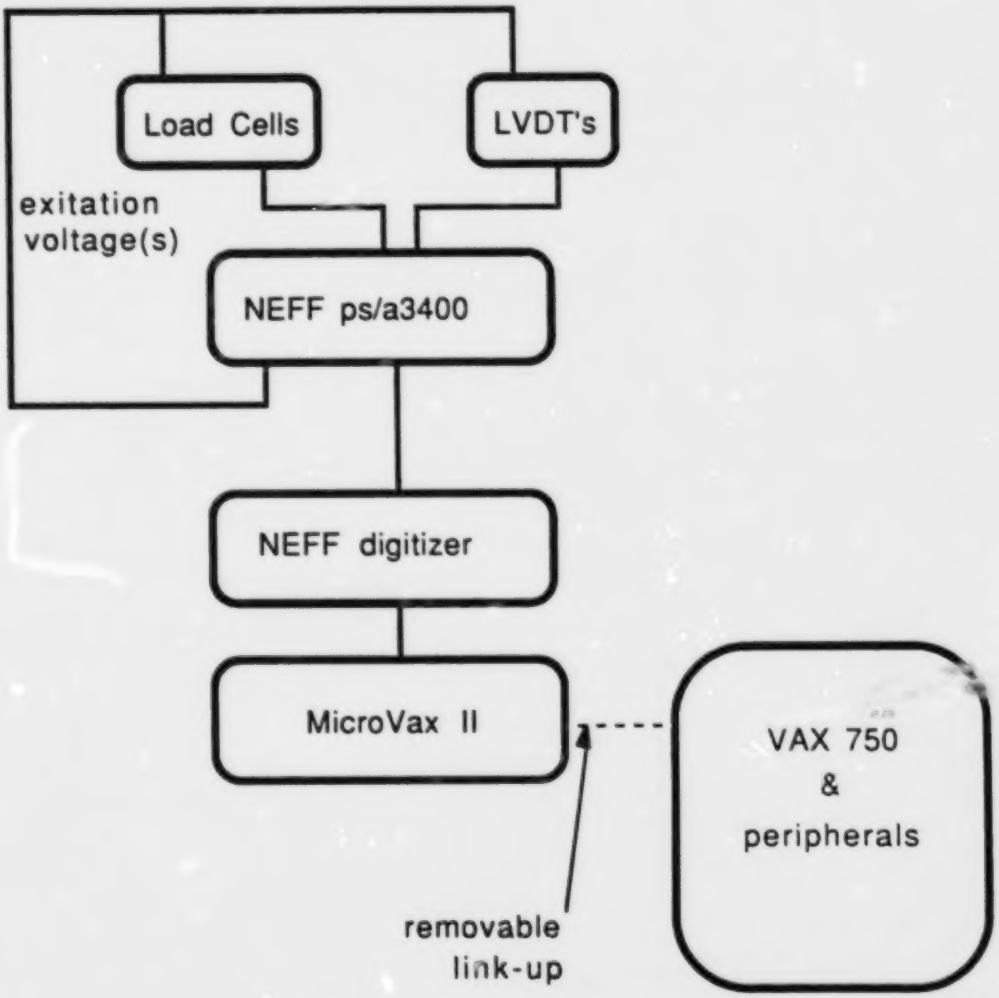
Presawn Pattern



The pre-sawn test measured the resistance of the model in ice that had no breaking strength. The submergence, clearing and friction along the midbody stayed essentially the same, thus comparison to level ice resistance allowed analysis of the breaking component alone.

5.0 DATA ACQUISITION

The resistance or tow force was measured using a load cell gimbal. The yaw load was measured using a load cell attached to a universal type swivel. The model motions were measured using LVDT's mounted on the tow post. The power supply for these sensors is handled by a NEFF system. The amplification of their output and digitizing of the measured signals is performed by another NEFF system. The digitized data is formatted and stored on disk by a MicroVAX computer system. For analysis and plotting, the data is transferred to a VAX750 computer. The figure below illustrates the schematic layout of the data acquisition system. A more complete description of the data acquisition system is available as an IMD lab memo(Ref. 8).



After a model test the data streams from the sensors are displayed on a graphics terminal on the towing carriage. This allows the operator to check the proper operation of the sensors, and allows extraction of preliminary resistance results.

6.0 DATA ANALYSIS

The first stage in data analysis consisted of examining the time series resistance data. Average resistance was calculated where the speed was constant. Accelerations of the towing carriage caused vibrations, which were visible as oscillations in the resistance record. The averages were taken from the time series record where these oscillations had died out, and a stable icebreaking mode was evident.

6.1 Results

A table presenting the averaged values of resistance, for both level unbroken ice and pre-sawn ice, as a function of speed is given in Appendix A. Other parameters pertinent to each test, such as the length and the surface finish of the model, ice thickness and ice strength are also presented. Plots of these resistance averages against speed were examined. These figures are presented in Appendix B.

The second stage of the data analysis involved a novel method for fitting smooth lines through the somewhat scattered data points. This method smoothed the data and corrected the measured values of resistance to target conditions of ice strength, thickness and density.

Conventional data analysis for resistance data involves correcting the resistance values based on the strength and thickness of the ice sheet using a linear correction technique. The variation in ice sheet thicknesses for the current tests was quite within usual norms, and a linear correction would be appropriate. On the other hand a wide variation in ice sheet strengths was observed. It was noted that the model resistance at low ice strengths was not as low as would be expected based on previous experience. This implies that the low strength measured using beams was not as apparent for the model. The usual linear correction method appears to over-correct the resistance in cases of weak ice.

The correction technique consisted of generating equations for the curves of the clearing component and the breaking component of the total resistance in ice. These equations are functions of thickness and strength, allowing correction of the resistance components to the target values of thickness and strength.

Dividing the resistance of the model in ice into three main components, the form resistance or viscous drag; the clearing resistance; and the breaking resistance, allowed these components to be treated separately and differently. The viscous drag on the model is a small component, it was calculated from the wetted surface area and the form coefficient:

$$R_f = \tfrac{1}{2}\, C_f\, \rho_w\, S\, V^2 \qquad (1)$$

where R_f = Form Resistance or Viscous Drag

ρ_w = Water Density

S = Wetted Surface Area

V = Speed of the Model

C_f = Form Coefficient = $0.075 / (\log(R_e)-2)$

R_e = Reynolds Number = $V L / \nu$

L = Length of the Model

ν = Kinematic Viscosity

When the viscous drag was subtracted from the pre-sawn resistance, the clearing resistance remained. The clearing component calculated in this manner was then subjected to a smoothing and correction technique.

The clearing component and the model speed were in effect non-dimensionalized using the expressions:

$$R_c / \rho_i B h V^2 \quad (2)$$

and

$$V/\sqrt{(g\ h)} \quad (3)$$

where R_c = Clearing Resistance

ρ_i = Density of the Model Ice (at the time of the pre-sawn test)

B = Beam of the Model

h = Thickness of the Model Ice

V = Speed of the Model

g = Acceleration due to Gravity

A log-log plot of these parameters produced a linear plot. Therefore a linear regression of the logs of the non-dimensional parameters was used to generate the coefficients α and β for the equation describing the clearing resistance:

$$R_c = \rho_i B h V^2 \cdot 10^{\beta} \cdot (V/\sqrt{(g\ h)})^{\alpha} \quad (4)$$

where α = the slope of the regression line

β = the intercept of the regression line

The clearing resistance had no dependence on ice strength because it expresses the resistance felt by a vessel passing through essentially zero strength ice. The dependence on ice thickness, evident from the above equation, was used later in the correction technique.

The next stage in the process was to (re-)generate values for the clearing component with the above equation, using the measured values of ice density and thickness. This stage in effect smoothed the data with a log-log fit. The smoothed clearing resistance values were then re-combined with their corresponding form resistance values, and subtracted from the total resistance measured in unbroken level ice. What remained was the third component, the breaking resistance.

A similar method was used for the analysis of the breaking resistance. The breaking component and model speed were non-dimensionalized using the expressions:

$$R_b / \rho_i B h V^2 \quad (5)$$

and

$$V/\sqrt{(\sigma/\rho_i)} \quad (6)$$

where σ = Ice Strength at the time of the level ice test

ρ_i = the ice density at the time of the level ice test.

Again a log-log plot of these parameters produced a linear plot. Therefore a linear regression of the logs of the non-dimensional parameters was used to generate coefficients for the equation describing the breaking resistance:

$$R_b = \rho_i B h V^2 \cdot 10^{\varepsilon} \cdot (V/\sqrt{(\sigma/\rho)})^{\delta} \qquad (7)$$

where δ = the slope of the regression line

ε = the intercept of the regression line

In this case the breaking resistance had a dependence both on the thickness and the strength of the ice. The parameter of greatest interest is the breaking resistance at the target conditions of thickness, strength and density. The measured values of breaking resistance were adjusted to the target conditions simply by substituting the target thickness, strength and density; eg. 30 mm, 19 kPa and 0.95 Mg/m^3 , into Equation 7.

Similarly the clearing resistance at target conditions was obtained simply by substituting the target values of thickness and density in Equation 4. The values of form resistance calculated earlier (Eq. 1) were then recombined with the clearing and breaking resistance values at target conditions to obtain the total resistance at target conditions.

7.0 DISCUSSION

This section deals with comparisons that can be made between tests within this program, as well as comparisons between this set of tests and the friction program tests. In closing, remarks are made comparing this data set to other length variation test programs. The graphs presenting the comparisons are contained in Appendix C.

7.1 Comparison of 50 mm Ice Sheets

Most of the tests from the friction program were run in 50 mm thick ice. A test in 50 mm thick ice was run in the midbody program for comparison purposes. The first figure in Appendix C illustrates these two test results. Both tests were of the full length model (whole midbody) with medium surface finishes and similar target strength and test speed (midbody test 1 and friction test 2). These two tests compare favorably, with a maximum difference of 11.3 %.

7.2 Comparison of 40 mm Ice Sheets

A 40 mm test was run in the midbody program for comparison to the third test in the friction program. The second figure in Appendix C illustrates these two test results. Both tests were of the full length model (whole midbody) with medium surface finishes and similar target strength and test speed. These two tests do not compare favorably. The corrected resistances for test 2 (midbody program) are as much as 71 % higher than those of test 3 (friction program). This is not considered representative of the actual test, but more of the correction method. The ice strength measurements show a markedly reduced strength, but this does not appear to have occurred. The data points as measured in test 2 (uncorrected) differ by a maximum of 12.8 % from those of friction test 3. When a least squares straight line is used to smooth the uncorrected data, the values exceed those of friction test 3 by only 3.1 %. The data values corrected with only a least squares straight line were used in subsequent comparisons.

7.3 Comparison of Medium and Rough Finish Models

As a follow up to the friction test program, a full length model with a rough bow and rough midbody was tested (test 4) in 30 mm model ice. The third figure in appendix C shows the results of this test compared to a medium finish model (test 1). The rough finish model has a significantly higher resistance at high speed.

7.4 Comparison of Three Finishes on Short Models (new bow)

The test series involving short models (in this case with the new bow) allows a comparison of the three surface finishes. The fourth graph in appendix C gives an overview of the effect of surface finish on these short models in 30 mm model ice. Test 5, rough finish, shows the highest resistance; test 7, medium finish, has an intermediate resistance; test 8, smooth finish, exhibits the lowest resistance.

7.5 Comparison of Three Finishes on Short Models (old bow)

The fifth graph in appendix C gives an overview of the effect of the three surface finishes on the short models with the old bow in 30 mm model ice. Test 6, rough finish, shows an intermediate resistance; test 10, medium finish, has the highest resistance; test 9, smooth finish, exhibits the lowest resistance. The reason for this inversion in not obvious, but the answer may lie in the amount of epoxy used to make the rough finish surface on the old bow. An excess of epoxy may have caused the surface to gloss over, giving a smoother than expected finish.

7.6 Comparison of Three Finishes on Short Models (combined)

The sixth graph in appendix C is simply an overlay of the two previous graphs. Note that the graph is presented slightly smaller than others to allow room for the legend on the page. This graph allows comparison of the two bows (old and new).

7.7 Comparison of Bows on the Standard Models

The seventh graph compares the two medium finish bows (old and new) on full midbody models in 30 mm model ice. The models were both medium finish. Test 3 is the new bow and test 11 is the old bow. The results clearly show the new bow with the full length model to be more effective.

7.8 Comparison of Bows on the Long Models

The eighth graph compares the two medium finish bows on 1 $^{2}/_{3}$ midbody models in 30 mm model ice. The models were both medium finish. Test 13 is the new bow and test 12 is the old bow. The results clearly show the new bow with the full length model to be more effective.

7.9 Comparison of Bows on the Standard & Long Models

The ninth graph in appendix C is simply an overlay of the two previous graphs. Note that the graph is presented slightly smaller than others to allow room for the legend on the page. This graph shows that the old and the new bow are not dramatically different with a standard model, and the old bow has a lower resistance than the new bow in the longer model configuration. This is in contrast to the results from the tests with short models (no midbody, comparison 6, above) where the old bow has a significantly higher resistance.

7.10 Comparison of Lengths for New Bow Models

Figure C.10 shows the length variation for medium finish models with the new bow in 30 mm model ice. The results are obscured by an apparent change in the speed dependence of resistance with increasing length. The lowest resistances are from test 7, the shortest model (no midbody). A straight line was plotted through these points to show the slope; the resistance increases slowly with increasing speed. There is an increased resistance with a slightly greater slope for test 14, half midbody, and again for test 3, full midbody. The results from test 13, 1 2/3 midbody, deviate from this pattern. A straight line was also plotted through these points, to show that the slope is much greater. The resistance of this long model is lower than expected for the two lower speeds, and rises above the other lengths for the two higher speeds.

7.11 Comparison of Lengths for Old Bow Models

The eleventh graph in appendix C shows the length variation for medium finish models with the old bow in 30 mm model ice. As above, straight lines were plotted through the data form the shortest and the longest models. The resistance of the longest model is lower than that of the shortest model, although the slope is greater (as in comparison 10). The resistance of the full midbody model is higher than that of the shortest model, as expected.

7.12 Comparison of Ice Thicknesses

The twelfth graph in appendix C shows the effect of model ice thickness on the resistance of a medium finish, full midbody model. This graph is essentially an overlay of the graphs of test 3 in 30 mm ice (appendix B); comparison 2, 40 mm ice; and comparison 1, 50 mm ice. The graph shows a reasonably consistent increase in resistance with increasing ice thickness.

7.13 Comparison with Other Studies

In a parametric model study of great lakes bulk carriers in ice (Ref. 5), three different model lengths were tested in three ice thicknesses. The data from this study was presented in graphical form, a copy of the graph is presented as the thirteenth graph in appendix C. The data is formatted as a percentage of the resistance of the middle length (normal) model. The length of a 1:25 scale model was varied from 3.96 to 6.34 to 8.72 meters, and the beam maintained at 0.91 meters. This gives L/B ratios of 4.4, 7.0, and 9.6 respectively. It appears that only the length of the parallel sided midbody was changed. In each of the three ice thicknesses, the shorter model's resistance was between 85 and 99 % of the resistance of the middle length model. For the longer model the resistance was more dependent on the ice thickness, as the resistance ranged from 120 to 180 % of the resistance of the middle length model for thin ice and from 130 to 150 % for medium and thick ice.

For comparison, the data from the present study was plotted as a percentage of the standard length model (full midbody) and presented as the fourteenth graph in appendix C.

A recently translated Japanese study on the effect of parallel body (Ref. 6) also employed three model lengths. The length of a 1:72 scale model was varied from 3.75 to 5.00 to 6.40 m, and the beam maintained at 0.722 m. This gives L/B ratios of 5.2, 6.9, and 8.9 respectively. Only the length of the parallel sided midbody was changed. Resistance vs length was presented for two model speeds. The results indicate a slight increase of resistance with length. Graphs from this study are presented as the fifteenth and sixteenth graphs in appendix C.

For comparison, the data from the present study, at comparable model speeds, are presented as the seventeenth and eighteenth graphs in appendix C.

7.14 Effect of Parallel Midbody Length on Resistance

The nineteenth graph in appendix C shows the effect of parallel midbody length on the resistance of a medium finish model with a new bow, in 30 mm thick model ice. The graph is essentially an overlay of the data from the four different model speeds.

REFERENCES

1 Froude, 1778

2 Comstock, J.P., Ed., Principles of Naval Architecture , SNAME, pg 309,1967.

3 Kitazawa, T. and R. Ettema, "Level Ice Resistance of an Icebreaking Ship with a Long, Parallel Middlebody", IIHR Lim. Distr. Report No. 120, Iowa Institute of Hydraulic Research, U. of Iowa, Aug.1984.

4 Edwards, R.Y.Jr., R.A. Major, J.K. Kim, J.G. German, J.W. Lewis and D.R. Miller, "Influence of Major Characteristics of Icebreaker Hulls on Their Powering Requirements and Maneuverability in Ice", SNAME Trans, V.84, pp.364-402,1976.

5 Voelker, R.P. and J.K. Kim, "Summary Results of Ice Resistance Tests for Great Lakes Bulk Carriers from the Wartsila Model Test Series", Arctec Incorporated Report No. 160C-1, Dec. 1976.

6 Williams, F.M., J.B. Snellen and J.M. Bell, "The Effect of Surface Friction on Ship Model Resistance in Level Ice", IMD/NRC Report TR-AVR-02, Apr. 1987.

7 Molyneux, W.D.,"M.V. Arctic and Two Alternative Bow Designs - Results of Resistance, Propulsion and Overload Experiments with Model Hulls 326,326B and 326C and Model Propeller 68", Arctic Vessel and Marine Research Institute, now IMD/NRC, Report LTR-SH-346, May 1983.

8 Thorburn, J.P., "Carriage Data Acquisition Hardware", IMD/NRC Report LM-RDS-04, Dec 1987.

9 Kitagawa, H., Y. Kokobo, S. Susuki, S. Miyajima, H. Shimoda and H. Tabuchi, "A Study on Ship Performance in Ice-Covered Waters (1st. Report) --Effect of Parallel Body--", Translation and Revision by H. Kitagawa available as IMD/NRC Report LM-AVR-14, Dec. 1986.

TABLE 1

FRICTION COEFFICIENTS FOR THE MODEL PARTS.

Test no.	Stern Plate	Mid-body Plate	2/3 Mid-body Plate	Smooth New Bow Plate	Smooth Old Bow Plate	Medium New Bow Plate (1A)	Medium Old Bow Plate	Rough Plate
1	0.13	0.16				0.063		
2		0.16						
3								
4	0.11							0.28
5								
6	0.12							0.25
7	0.12					0.049		
8	0.13			0.03				
9	0.13				0.0026			
10								
11	0.13	0.18						
12	0.11	0.14	0.17				0.14	
	0.09							
13	0.12	0.15	0.16			0.054		
						0.053		
14	0.12		0.16			0.062		
			0.13			0.061		

Plates of plywood were prepared and painted with the same surface finish as the corresponding model parts. These plates were tested with model ice in the friction jig to determine the friction coefficient. The results are presented in the above table. The test numbers correspond to the model test performed in the tank. The stern, midbody sections and the medium finish old bow were all painted for this program at about the same time. The smooth and medium new bows were painted in late 1986, for the friction program. The plates from the friction program were re-tested and the results included in the table above.

MODEL SPECIFICATIONS FOR EACH TEST

Test No.	Displacement (kg)	GM (m)	Roll Period (s)	Pitch Period (s)
1	1393.4	0.053	2.55	1.5
2	1393.4	0.053	2.55	1.5
3	1393.4	0.053	2.55	1.5
4	1393.4	0.0524	2.55	1.5
5	616.3	0.0477	2.78	1.88
6	602.4	0.0498	2.4	1.82
7	616.3	0.054	2.55	1.7
8	616.3	0.0466	2.67	1.38
9	602.4	0.049	2.54	1.74
10	602.4	0.052	2.28	1.74
11	1379.5	0.0519	2.55	1.5
12	1851.1	0.0486	2.72	1.5
13	1865.0	0.0506	2.60	1.52
14	1039.6	0.0493	2.6	1.6

GM, Pitch and Roll periods were measured with the model ballasted and in the tank. The GM was measured by inclining. For all the above tests, the target GM was 0.05 m. The target value for roll period was 2.55 s, and for all except the short models (5 through 10) the target pitch period was 1.48 s. For short models a longer pitch period of 1.87 s was attempted.

MODEL TEST PROGRAM MATRIX

\ Model Section / Test\	Melville Bow (new)	Original Bow (old)	1/2 Mid Body	Whole Mid Body	1 2/3 Mid Body	Stern	Ice Thickness (mm)	Date
1	M			M		M	50	Jan 19
2	M			M		M	40	Jan 21
3	M			M		M	30	Jan 22
4	R			R		M	50	Jan 26
5	R					M	30	Jan 28
6		R				M	30	Jan 29
7	M					M	30	Feb 2
8	S					M	30	Feb 3
9		S				M	30	Feb 4
10		M				M	30	Feb 5
11		M		M		M	30	Feb 9
12		M			M	M	30	Feb 10
13	M				M	M	30	Feb 11
14	M		M			M	30	Feb 12

Surface Finishes: R - Rough
M - Medium
S - Smooth

MONITORING OF MODEL ICE - RESULTS OF ICE FLEXURAL STRENGTH TESTS.

Test No.	Nominal Ice Strength (kPa) At Test Time	
	Level Ice Test	Presawn Ice Test
1	17.3	13.0
2	15.1	9.2
3	18.0	9.3
4	18.2	12.7
5	24.0	15.6
6	22.3	14.8
7	22.5	13.5
8	21.9	16.9
9	21.8	13.1
10	17.5	9.9
11	25.8	11.3
12	21.8	17.8
13	19.8	17.0
14	26.0	12.7

OVERVIEW OF THE MODEL SECTIONS

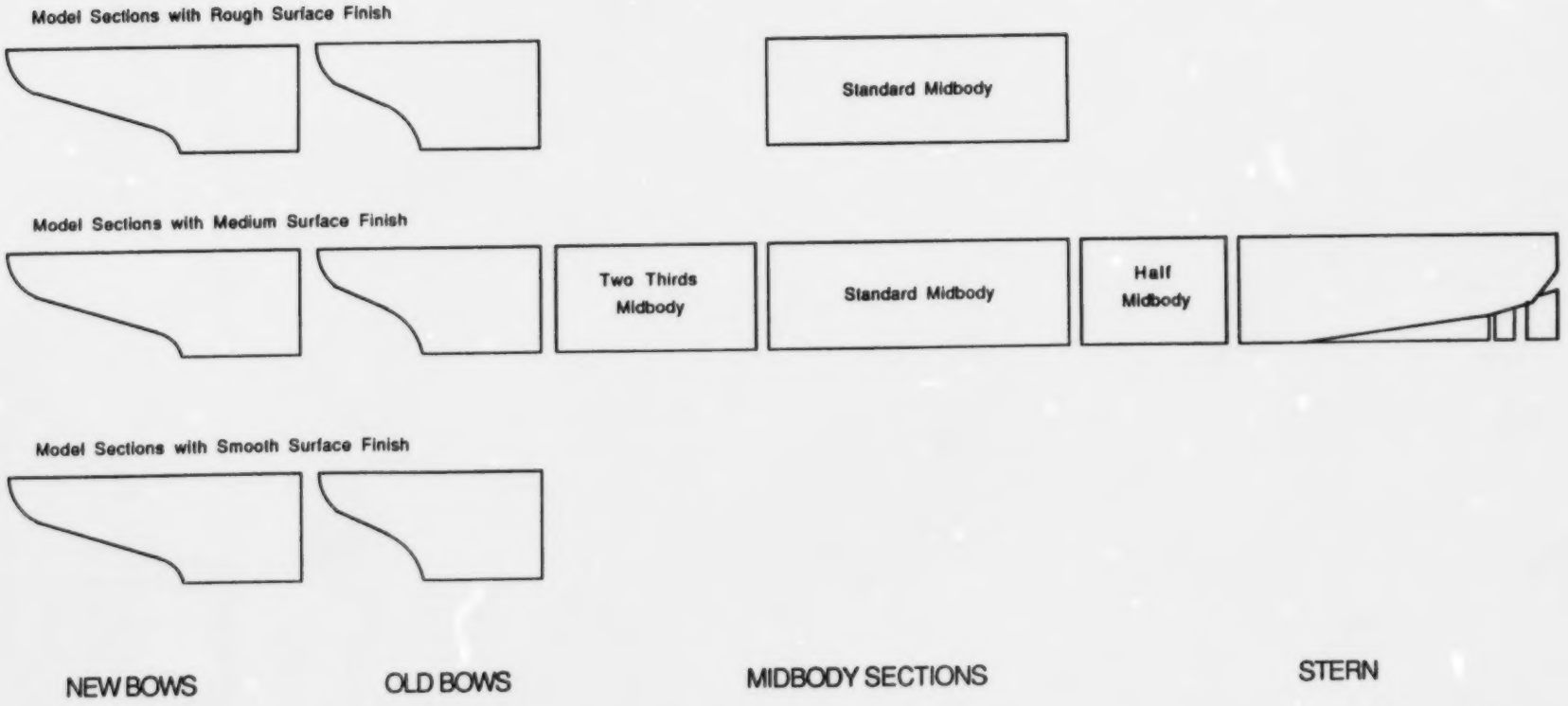


Figure 1

APPENDIX A

Tabulated Data

Guide to Appendix A

Appendix A is a compilation of the ice tank measurements made for the parallel midbody test program. The measurements are followed by a suite of calculations designed to smooth the resistance measurements and fit fair lines to the data.

The appendix is presented in spreadsheet format, and is six pages wide and three pages long (18 pages total). The column headings and row labels were not repeated on each page.

It should be noted that this appendix includes some data from the friction program. Two tests of the medium finish, standard length model were included at the end of the appendix for comparison purposes.

Column A indicates the test number, which identifies all the data collected on a test day.

Column B gives the run number, identifying runs of the level ice test. (col. J also gives run numbers, but for presawn ice tests).

Column C date.

Column D test time (GMT) for the level ice test run(s), as provided by the data acquisition system.

Column E indicates the averaged ice thickness (16 readings) measured in the test zone applicable to that row. The target thicknesses were 50, 40 and 30 mm.

Column F indicates the averaged ice strength (10 readings) measured in the test zone applicable to that row. The target strength was 19 kPa throughout the test program.

Column G indicates the speed at which the model was tested. Speed is the independent variable in this test series. A slow speed run was included in each test (0.02 m/s), but not considered in the analysis of the data.

Column H gives the averaged total resistance to motion (force) measured by the towing gimbal, when the model was moved through level ice at the speed given in column G. See Note 1. Resistance is the dependent variable in this test series.

Column I is a preliminary reading of the resistance, as taken from the screen of the data acquisition computer. See Note 2.

Column J gives the run number, for runs of the presawn ice test.

Column K test time for the presawn run(s)

Column L gives the ice density. The first number in the column is the measured ice density, and below it is the tempering time, in decimal hours (H.h) . Reading down the column, the number following the blank is the calculated ice density, corrected to the time of the presawn test, and below it is the tempering time of the presawn test in decimal hours. See Note 3.

Column M gives the average resistance to motion measured when the model moves through presawn ice at the speed given in column G.

Column N illustrates the repeatability of calculating the average resistance. The average presawn resistance was generated for the data from test 4, run 2 on two separate occasions, with good agreement.

Column O is a preliminary reading of the resistance, as taken from the screen of the data acquisition computer.

Column P shows the difference between the resistance and the presawn resistance, the Ice Breaking component. It is given here solely for comparison to the smoothed breaking resistance presented in column AI.

Column Q describes the models that were tested. The coding for the first line is as follows:

nb	new bow
ob	old bow
mb	standard midbody
0.5mb	half-length midbody
1.7mb	1 2/3 length midbody
s	stern

The second line contains coding for the surface finishes of the respective parts above.

s	smooth
m	medium
r	rough

Column R gives the waterline length of the model for calculation of the wetted surface.

Column S calculates the length to beam ratio, based on a beam of 0.762 meters, the same for each model.

Column T calculated wetted surface.

Column U calculated Reynolds Number.

Column V Form coefficient.

Column W calculated viscous drag, or form drag, due to hull/water interaction (Eqn. 1).

Column X resistance of the model due to the process of clearing the ice out of the way. (Presawn resistance without the viscous drag).

Column	Y	log of non-dimensional clearing resistance (Eqn. 2).
Column	Z	log of non-dimensional speed (Eqn. 3).
Column	AA	linear regression coefficient of column Y vs column Z. The slope of the line.
Column	AB	linear regression coefficient of column Y vs column Z. The intercept of the line.
Column	AC	smoothed clearing resistance calculated from the linear regression (Eqn. 4).
Column	AD	resistance of the model due to the process of breaking the ice. (Total resistance without the presawn resistance or the viscous drag).
Column	AE	log of non-dimensional breaking resistance (Eqn. 5).
Column	AF	log of non-dimensional speed (Eqn. 6).
Column	AG	linear regression coefficient of column AE vs column AF. The slope of the line.
Column	AH	linear regression coefficient of column AE vs column AF. The intercept of the line.
Column	AI	smoothed breaking resistance calculated from the linear regression (Eqn. 7).
Column	AJ	breaking component re-calculated from Equation 7 with the density, thickness and strength of the ice at target values.
Column	AK	clearing component re-calculated from Equation 4 with the density and thickness of the ice at target values.
Column	AL	gives the calculated density of the ice corrected to the time of the level ice test (supplements column L).
Column	AM	sums the breaking and clearing resistances at target conditions with the viscous drag, for a total resistance based on target conditions of density, thickness and strength.
Column	AN	repeats the total resistance measured (column H), for comparison.
Column	AO	presents the resistance corrected using conventional methods, as per D. Baker, for comparison.
Column	AP	presents the presawn resistance corrected using conventional methods, as per D. Baker, for comparison.

Note 1 The resistances reported in the column were generated from the time series of resistance recorded during the test: a section of the record where the speed was constant, and acceleration induced vibrations were not evident, was averaged. This provided the value of resistance for that speed.

Note 2 The preliminary resistances are included only to show that they are less reliable. Preliminary resistance would not be used for calculations under normal circumstances.

Note 3 Because the density of EGAD ice is time dependent, the time reported with the density is the time of the measurement. This time is expressed as tempering time, the elapsed time since the freezing/growing process was halted.

The density was corrected to the time of the presawn test for use in calculating the clearing resistance. For calculating the breaking resistance, the density was corrected to the level ice test time (column AL). The correction used the measured density and test times expressed in tempering time and was based a least squares straight line generated from all the ice density and tempering time information available for comparable ice sheets in our ice tank.

	A	B	C	D	E	F	G	H	I
1	test	run	date	time	ice	ice	speed	resistance	resistance
2	no.	no.		gmt	thickness	strength	m/s	Newtons	Newtons
3				(L+3.5)	mm	kPa			prelim.
4					h/1000	sigma	V	Rt	
5	1	1	19 jan 88	19:20	51.4	21.8	0.188	86.7	93
6					51.7	22.4	0.329	121.3	118
7					52.5	18.6	0.470	113.1	126
8					51.4	28.6	0.600	162.7	150
9		2		19:29	51.4	28.6	0.010		140
10					51.4	28.6	0.010	98.6	107
11									
12	2	1	21 jan 88	13:58	40.6	10.9	0.189	54.0	55
13					40.5	13.6	0.329	73.2	74
14					41.4	13.4	0.470	83.6	80
15					40.5	17.5	0.600	76.3	80
16					40.5	17.5	0.020	39.8	38
17									
18	3	1	22 jan 88	13:38	30.7	11.1	0.189	35.4	35
19					30.7	13.5	0.329	41.4	43
20					30.7	15.8	0.470	53.6	52
21					29.9	17.2	0.600	59.7	56
22					29.9	17.2	0.020	17.5	22
23									
24	4	1	26 jan 88	18:19	50.6	15.8	0.189	117.9	148
25					50.6	15.8	0.189	145.7	
26					50.5	20.1	0.329	187.2	205
27					51.3	18.6	0.470	229.0	238
28					50.4	25.1	0.600	349.3	357
29					50.4	25.1	0.020	277.9	
30					50.4	25.1	0.020	188.6	223
31									
32	5	1	28 jan 88	14:12	31.1	18.9	0.189	67.3	84.8
33					31.1	22.4	0.329	78.4	82.5
34					31.1	25.7	0.470	100.6	100.6
35					30.9	28.4	0.600	111.4	112.7
36					30.9	28.4	0.020	77.9	
37					30.9	28.4	0.020	34.5	35.8
38									
39	6	1	29 jan 88	14:22	31.1	15.5	0.189	58.8	61.9
40					31.1	18.4	0.329	69.0	86.5
41					31.1	21.3	0.470	85.4	82.9
42					31.2	22.5	0.600	92.8	92.3
43					31.2	22.5	0.020	35.0	62.1
44									

	J	K	L	M	N	O	P	Q	R
1	run	time	Ice	presawn		presawn	I.B.	model/	length
2	no.		density	resistance		resistance	comp	finishes	m
3			Mg/m^3	Newtons		prelim	Newtons		(LWL)
4			ro	Rps			(Rt-Rps)		L
5	3	21:07	0.939	31.1		31	55.6	nb/mb/s	7.011
6			14.11	44.5		43	76.8	m/m/m	7.011
7				49.7		50	63.4		7.011
8			0.942	54.2		54	108.5		7.011
9	4	21:17	15.33	22.7		22.2			
10				10.9			87.7		7.011
11									
12	2	15:38	0.946	18.2		18	35.8	nb/mb/s	7.011
13			12.87	26.1		26	47.1	m/m/m	7.011
14				35.7		38	47.9		7.011
15			0.949	39.6		39	36.7		7.011
16			14	13.7		14	26.1		7.011
17									
18	2	15:12	0.951	12.4		12	23.0	nb/mb/s	7.011
19			10.12	17.0		18	24.4	m/m/m	7.011
20				23.7		24	29.9		7.011
21			0.954	29.7		30	30.0		7.011
22			11.17	7.1		7	10.4		7.011
23									
24	2	19:57	0.939	61.8	61.6	62	56.1	nb/mb/s	7.011
25			12.98					r/r/m	
26				75.2	75.2	73	112.0		7.011
27			0.942	86.2	79.3	82	142.8		7.011
28			14	105.0	105.7	104	244.3		7.011
29				54.2					
30	3	20:06		66.7		66	121.9		7.011
31									
32	2	15:44	0.946	26.0		26	41.3	nb/s	4.596
33			9.88	32.4		32.7	46.0	r/m	4.596
34				42.6		42.6	58.0		4.596
35			0.948	51.9		51.9	59.5		4.596
36			10.81	17.4		15.1	60.5		4.596
37									
38									
39	2	15:48	9.48	17.8		18	41.0	ob/s	4.279
40			10.3	22.9		23.1	46.1	r/m	4.279
41				30.6		29.8	54.8		4.279
42			0.949	37.0		37.2	55.8		4.279
43			10.73	14.7		18.6	20.3		4.279
44									

	S	T	U	V	W	X	Y	Z
1	length to	wetted	Reynolds	Form	Viscous	Clearing	Log [Rc/	log [V/
2	beam ratio	surface	Number	Coeff.	Drag	Newtons	ro B h V^2]	root(g h)]
3	B=0.762	sq m			Newtons	(Rps - Rf)		
4	L/B		RE	Cf	Rf	Rc		
5	9.2	8.087	7.38E+05	5.01E-03	0.7	30.4	4.37	-0.577
6	9.2	8.087	1.29E+06	4.44E-03	1.9	42.6	4.03	-0.335
7	9.2	8.087	1.84E+06	4.12E-03	3.7	46.0	3.74	-0.184
8	9.2	8.087	2.35E+06	3.92E-03	5.7	48.5	3.56	-0.073
9								
10	9.2	8.087	3.92E+04	1.11E-02	0.0	10.9	6.47	-1.851
11								
12	9.2	8.087	7.42E+05	5.01E-03	0.7	17.5	4.22	-0.524
13	9.2	8.087	1.29E+06	4.44E-03	1.9	24.2	3.88	-0.282
14	9.2	8.087	1.84E+06	4.12E-03	3.7	32.0	3.68	-0.132
15	9.2	8.087	2.35E+06	3.92E-03	5.7	33.9	3.51	-0.021
16	9.2	8.087	7.85E+04	8.95E-03	0.0	13.7	6.07	-1.499
17								
18	9.2	8.087	7.42E+05	5.01E-03	0.7	11.7	4.17	-0.463
19	9.2	8.087	1.29E+06	4.44E-03	1.9	15.1	3.79	-0.222
20	9.2	8.087	1.84E+06	4.12E-03	3.7	20.0	3.61	-0.067
21	9.2	8.087	2.35E+06	3.92E-03	5.7	24.0	3.49	0.044
22	9.2	8.087	7.85E+04	8.95E-03	0.0	7.1	5.91	-1.433
23								
24	9.2	8.087	7.42E+05	5.01E-03	0.7	61.1	4.67	-0.571
25								
26	9.2	8.087	1.29E+06	4.44E-03	1.9	73.3	4.27	-0.330
27	9.2	8.087	1.84E+06	4.12E-03	3.7	82.5	4.01	-0.179
28	9.2	8.087	2.35E+06	3.92E-03	5.7	99.3	3.88	-0.069
29								
30	9.2	8.087	7.85E+04	8.95E-03	0.0	66.7	6.66	-1.546
31								
32	6.0	4.634	4.86E+05	5.52E-03	0.5	25.5	4.50	-0.466
33	6.0	4.634	8.46E+05	4.86E-03	1.2	31.2	4.11	-0.225
34	6.0	4.634	1.21E+06	4.50E-03	2.3	40.3	3.91	-0.070
35	6.0	4.634	1.54E+06	4.28E-03	3.6	48.3	3.78	0.037
36	6.0	4.634	5.14E+04	1.02E-02	0.0	17.4	6.29	-1.440
37								
38								
39	5.6	4.436	4.53E+05	5.61E-03	0.4	17.4	4.33	-0.466
40	5.6	4.436	7.88E+05	4.94E-03	1.2	21.7	3.95	-0.225
41	5.6	4.436	1.13E+06	4.57E-03	2.2	28.4	3.76	-0.070
42	5.6	4.436	1.44E+06	4.34E-03	3.5	33.5	3.62	0.035
43	5.6	4.436	4.79E+04	1.04E-02	0.0	14.7	6.21	-1.442
44								

	AA	AB	AC	AD	AE	AF
1	Regr. Coef.	Regr. Coef.	Smoothed	Breaking	log [Rb/	log [V/
2	of Y vs Z	of Y vs Z	Clearing	Component	ro B h V^2]	√(sigma/ro)]
3			Component	Rt-Rc-Rf		
4	A	B	Rc	Rb		
5	-1.608	3.454	31.4	54.6	4.62	-1.409
6			39.6	79.8	4.30	-1.172
7			46.8	62.7	3.88	-0.977
8			49.5	107.5	3.91	-0.964
9						
10			10.0	88.6	7.38	-2.742
11						
12	-1.409	3.486	17.6	35.7	4.53	-1.254
13			24.3	47.0	4.17	-1.061
14			31.1	48.8	3.87	-0.903
15			34.6	36.0	3.53	-0.855
16			4.6	35.1	6.48	-2.332
17						
18	-1.527	3.460	11.7	23.0	4.46	-1.257
19			15.2	24.2	4.00	-1.059
20			18.0	31.9	3.81	-0.938
21			19.3	34.7	3.65	-0.851
22			3.9	13.6	6.20	-2.328
23						
24	-1.626	3.732	59.5	57.7	4.65	-1.337
25						
26			72.9	112.4	4.46	-1.149
27			85.7	139.6	4.24	-0.977
28			90.9	252.6	4.29	-0.936
29						
30			25.5	163.1	7.05	-2.413
31						
32	-1.442	3.814	24.6	42.3	4.72	-1.374
33			33.4	43.7	4.26	-1.170
34			40.8	57.5	4.07	-1.045
35			46.3	61.6	3.89	-0.961
36			6.9	71.0	6.90	-2.438
37						
38						
39	-1.430	3.655	16.8	41.5	4.72	-1.331
40			23.1	44.7	4.27	-1.127
41			28.3	54.9	4.05	-1.004
42			32.7	56.7	3.85	-0.910
43			4.7	30.3	6.53	-2.387
44						

	AG	AH	AI	AJ	AK	AL	AM
1	Regr. Coef.	Regr. Coef.	Smoothed	Breaking	Clearing	Density at	Total
2	of AE vs AF	of AE vs AF	Breaking	Component	Component	Test Time	Resistance
3			Component	at Target	at Target	(av dens	at Target
4	C	D	Rb	Conditons	Conditons	0.945)	Conditons
5	-1.683	2.275	57.6	51.1	30.2	0.937	82.0
6			70.7	61.0	37.6		100.5
7			68.8	68.3	43.2		115.2
8			104.5	73.8	47.5		127.0
9							
10			28.6	20.2	9.5		29.7
11							
12	-2.303	1.683	39.0	75.0	17.1	0.945	92.9
13			42.4	63.4	23.8		89.1
14			38.3	56.9	29.4		90.0
15			47.3	52.9	33.9		92.5
16			132.6	148.2	4.5		152.7
17							
18	-1.988	1.942	21.9	37.5	11.2	0.95	49.4
19			26.8	37.7	14.5		54.2
20			31.5	37.9	17.2		58.8
21			33.4	38.0	19.3		63.1
22			32.1	36.4	3.9		40.3
23							
24	-0.999	3.311	57.1	37.9	23.2	0.937	61.9
25							
26			112.0	66.0	28.6		96.5
27			156.5	94.3	32.7		130.7
28			228.0	120.5	35.8		162.0
29							
30			7.6	4.0	10.0		14.0
31							
32	-2.002	1.956	40.7	40.5	23.1	0.944	64.1
33			48.2	40.5	31.5		73.2
34			55.3	40.5	38.4		81.2
35			60.7	40.4	44.1		88.1
36			61.1	40.7	6.6		47.3
37							
38							
39	-2.052	1.975	40.7	49.6	15.8	0.945	65.9
40			47.1	48.2	21.7		71.1
41			53.7	47.3	26.6		76.2
42			56.3	46.7	30.6		80.8
43			67.2	55.8	4.4		60.2
44							

	AN	AO	AP	AQ
1	resistance	Baker	Baker	
2	Newtons	corrected	corrected	
3		resistance	presawn	
4	Rt			
5	86.7	76.526	29.742	
6	121.3	92.5	42.274	
7	113.1	107.64	46.718	
8	162.7	119.573	52.605	
9				
10	98.6	67.609	21.03	
11				
12	54.0	58.764	17.409	
13	73.2	71.177	25.095	
14	83.6	80.426	33.185	
15	76.3	90.334	38.84	
16	39.8	37.757	13.031	
17				
18	35.4	40.54	11.771	
19	41.4	49.487	16.083	
20	53.6	57.745	22.865	
21	59.7	63.319	29.814	
22	17.5	18.999	7.169	
23				
24	117.9	127.502	60.725	
25				
26	187.2	178.391	74.094	
27	229.0	224.887	83.511	
28	349.3	285.984	104.811	
29	277.9			
30	188.6	156.09	65.86	
31				
32	67.3	63.721	23.928	
33	78.4	65.903	29.655	
34	100.6	79.844	40.242	
35	111.4	83.661	50.108	
36	77.9	42.795	15.871	
37	34.5			
38				
39	58.8	64.74	16.381	
40	69.0	65.649	20.96	
41	85.4	74.699	28.906	
42	92.8	75.184	35.296	
43	35.0	22.808	12.978	
44				

	A	B	C	D	E	F	G	H	I
45	7	1	2 feb 88	14:15	30.1	13.0	0.189	31.5	31.8
46					30.3	20.8	0.329	40.7	40.1
47					30.6	21.5	0.470	48.0	48.1
48					29.4	23.4	0.600	49.5	49
49					29.4	23.4	0.020	21.4	22.9
50									
51	8	1	3 feb 88	14:11	30.0	20.4	0.189	21.4	20.9
52					30.4	20.2	0.329	23.3	23.3
53					30.2	14.9	0.470	26.7	25.5
54					29.3	22.9	0.600	30.1	30.4
55					29.3	22.9	0.020	12.4	12.5
56									
57	9	1	4 feb 88	14:03	30.9	12.9	0.189	25.8	26.1
58					31.0	14.5	0.329	34.0	34.1
59					31.3	19.1	0.470	46.7	45.3
60					30.0	20.2	0.600	47.9	48.6
61					30.0	20.2	0.020	14.5	12.6
62									
63	10	1	5 feb 88	14:04	30.3	13.0	0.189	81.6	82.6
64					30.2	22.8	0.329	85.4	87.3
65					30.9	17.7	0.470	114.9	116.3
66					29.6	19.9	0.600	102.2	108.3
67					29.6	19.9	0.020	39.1	36
68									
69	11	1	9 feb 88	14:30	30.2	18.0	0.189	103.1	98
70					30.2	19.2	0.329	103.5	101
71					30.1	23.2	0.470	133.9	129
72					29.4	19.8	0.600	119.5	120
73					29.4	19.8	0.020	68.4	57
74									
75	12	1	10 feb 88	14:07	30.2	15.7	0.189	64.2	57
76					30.0	18.9	0.329	89.1	84
77					30.6	19.7	0.470	110.5	108
78					29.4	24.9	0.600	107.5	109
79					29.4	24.9	0.020	35.4	40
80									
81	13	1	11 feb 88	14:13	29.4	15.9	0.189	32.7	38
82					29.4	17.6	0.329	50.5	59
83					29.5	21.4	0.470	56.6	59
84					29.0	20.5	0.600	78.6	76
85					29.0	20.5	0.020	25.4	
86					29.0	20.5	0.020	21.4	20
87					29.0	20.5	0.020	16.6	
88									

	J	K	L	M	N	O	P	Q	R
45	2	15:39	9.49	16.8		16.1	14.7	nb/s	4.596
46			10.15	22.8		22.9	17.9	m/m	4.596
47				30.6		31	17.4		4.596
48			0.95	36.2		36.3	13.3		4.596
49			10.72	11.8		11.7	9.6		4.596
50									
51	2	15:34	0.95	6.4	6.4	6.6	15.0	nb/s	4.596
52			10.29	9.3	9.3	8.3	14.0	s/m	4.596
53				14.2	14.1	14.2	12.5		4.596
54			0.951	20.5	20.5	21	9.6		4.596
55			10.82	4.7	5.1	4.7	7.7		4.596
56									
57	2	15:30	0.947	10.2		10.3	15.6	ob/s	4.279
58			9.79	13.9		13.8	20.1	s/m	4.279
59				17.4		17.5	29.3		4.279
60			0.951	21.9		21.8	26.0		4.279
61			10.72	6.5		7.5	8.0		4.279
62									
63	2	15:27	0.946	30.1		30.2	51.5	ob/s	4.279
64			9.63	33.1		33.9	52.3	m/m	4.279
65				42.3		42.7	72.6		4.279
66			0.949	46.2		47.1	56.0		4.279
67			10.53	25.1		21.9	14.0		4.279
68									
69	2	15:45	0.949	32.9		33	70.2	ob/mb/s	6.694
70			10.3	42.8		42	60.7	m/m/m	6.694
71				45.6		48	88.3		6.694
72			0.951	47.6		48	71.9		6.694
73			11.01	15.2		16	53.2		6.694
74									
75	2	15:25	0.948	30.4		30	33.8	ob/1.7mb	8.423
76			9.93	35.4		35	53.7	m/m/m	8.423
77				42.0		43	68.5		8.423
78			0.95	47.0		48	60.5		8.423
79			10.8	20.7		20	14.7		8.423
80									
81	2	15:33	0.95	14.7		14	18.0	nb/1.7mb	8.740
82			10.13	19.3		20	31.2	m/m/m	8.740
83				27.9		28	28.7		8.740
84			0.953	34.3		34	44.3		8.740
85			11.05						
86									
87				9.2		9	7.4		8.740
88									

	S	T	U	V	W	X	Y	Z
45	6.0	4.634	4.86E+05	5.52E-03	0.5	16.3	4.32	-0.459
46	6.0	4.634	8.46E+05	4.86E-03	1.2	21.6	3.96	-0.219
47	6.0	4.634	1.21E+06	4.50E-03	2.3	28.3	3.76	-0.067
48	6.0	4.634	1.54E+06	4.28E-03	3.6	32.6	3.63	0.048
49	6.0	4.634	5.14E+04	1.02E-02	0.0	11.8	6.14	-1.429
50								
51	6.0	4.634	4.86E+05	5.52E-03	0.5	5.9	3.88	-0.458
52	6.0	4.634	8.46E+05	4.86E-03	1.2	8.1	3.53	-0.220
53	6.0	4.634	1.21E+06	4.50E-03	2.3	11.9	3.39	-0.064
54	6.0	4.634	1.54E+06	4.28E-03	3.6	16.9	3.35	0.049
55	6.0	4.634	5.14E+04	1.02E-02	0.0	4.7	5.74	-1.428
56								
57	5.6	4.436	4.53E+05	5.61E-03	0.4	9.8	4.09	-0.464
58	5.6	4.436	7.88E+05	4.94E-03	1.2	12.7	3.72	-0.224
59	5.6	4.436	1.13E+06	4.57E-03	2.2	15.2	3.48	-0.072
60	5.6	4.436	1.44E+06	4.34E-03	3.5	18.4	3.37	0.044
61	5.6	4.436	4.79E+04	1.04E-02	0.0	6.5	5.87	-1.433
62								
63	5.6	4.436	4.53E+05	5.61E-03	0.4	29.7	4.58	-0.460
64	5.6	4.436	7.88E+05	4.94E-03	1.2	31.9	4.13	-0.219
65	5.6	4.436	1.13E+06	4.57E-03	2.2	40.1	3.91	-0.069
66	5.6	4.436	1.44E+06	4.34E-03	3.5	42.7	3.74	0.047
67	5.6	4.436	4.79E+04	1.04E-02	0.0	25.1	6.47	-1.430
68								
69	8.8	7.889	7.08E+05	5.06E-03	0.7	32.2	4.61	-0.459
70	8.8	7.889	1.23E+06	4.48E-03	1.9	40.9	4.24	-0.219
71	8.8	7.889	1.76E+06	4.16E-03	3.6	42.0	3.94	-0.063
72	8.8	7.889	2.25E+06	3.96E-03	5.6	42.0	3.74	0.048
73	8.8	7.889	7.49E+04	9.08E-03	0.0	15.2	6.25	-1.429
74								
75	11.1	10.362	8.91E+05	4.81E-03	0.9	29.5	4.58	-0.459
76	11.1	10.362	1.55E+06	4.27E-03	2.4	33.0	4.15	-0.217
77	11.1	10.362	2.22E+06	3.97E-03	4.5	37.5	3.88	-0.067
78	11.1	10.362	2.83E+06	3.78E-03	7.1	39.9	3.72	0.048
79	11.1	10.362	9.43E+04	8.48E-03	0.0	20.7	6.39	-1.429
80								
81	11.5	10.56	9.25E+05	4.77E-03	0.9	13.8	4.26	-0.454
82	11.5	10.56	1.61E+06	4.24E-03	2.4	16.9	3.86	-0.213
83	11.5	10.56	2.30E+06	3.94E-03	4.6	23.3	3.69	-0.059
84	11.5	10.56	2.94E+06	3.76E-03	7.1	27.2	3.55	0.051
85								
86								
87	11.5	10.56	9.78E+04	8.39E-03	0.0	9.2	6.04	-1.426
88								

	AA	AB	AC	AD	AE	AF
45	-1.374	3.679	15.9	15.2	4.29	-1.292
46			22.7	16.8	3.85	-1.154
47			28.8	16.9	3.54	-1.006
48			31.4	14.5	3.28	-0.918
49			3.7	17.7	6.32	-2.395
50						
51	-1.087	3.349	5.5	15.5	4.30	-1.390
52			9.2	12.8	3.73	-1.147
53			12.7	11.7	3.39	-0.926
54			15.1	11.4	3.18	-0.913
55			0.7	11.7	6.14	-2.390
56						
57	-1.435	3.407	9.5	15.9	4.30	-1.291
58			13.0	19.8	3.91	-1.076
59			16.2	28.3	3.75	-0.980
60			17.3	27.1	3.54	-0.887
61			2.5	12.0	6.14	-2.364
62						
63	-1.651	3.801	28.5	52.7	4.83	-1.293
64			34.3	49.9	4.33	-1.174
65			40.5	72.1	4.17	-0.964
66			40.8	57.9	3.88	-0.884
67			12.5	26.6	6.49	-2.361
68						
69	-1.671	3.815	29.9	72.5	4.97	-1.363
70			35.9	65.7	4.44	-1.136
71			40.1	90.2	4.27	-1.022
72			41.6	72.3	3.98	-0.882
73			13.6	54.8	6.81	-2.359
74						
75	-1.710	3.784	29.0	34.3	4.64	-1.333
76			33.6	53.1	4.36	-1.133
77			38.7	67.3	4.14	-0.987
78			38.5	61.9	3.91	-0.932
79			14.4	21.0	6.39	-2.409
80						
81	-1.387	3.608	13.2	18.6	4.39	-1.336
82			18.5	29.6	4.11	-1.117
83			23.1	28.9	3.79	-1.004
84			26.1	45.3	3.78	-0.889
85						
86						
87			3.2	13.3	6.20	-2.366
88						

	AG	AH	AI	AJ	AK	AL	AM
45	-2.636	0.860	14.3	24.4	15.8	0.947	40.6
46			18.8	17.1	22.3		40.7
47			15.8	13.6	27.9		43.9
48			14.6	11.7	32.5		47.8
49			126.8	101.6	3.9		105.5
50							
51	-2.161	1.285	15.0	14.3	5.5	0.948	20.2
52			13.8	13.1	9.0		23.4
53			9.3	12.4	12.5		27.2
54			13.8	11.9	15.7		31.1
55			23.9	20.6	0.7		21.3
56							
57	-1.847	1.923	16.1	22.9	9.0	0.946	32.4
58			19.6	24.9	12.3		38.4
59			27.0	26.3	15.0		43.6
60			28.2	27.4	17.3		48.1
61			16.8	16.2	2.5		18.8
62							
63	-2.013	2.129	42.0	62.5	28.0	0.945	90.9
64			73.1	62.0	33.9		97.2
65			57.7	61.8	38.4		102.4
66			62.0	61.6	41.9		106.9
67			64.7	64.3	12.8		77.1
68							
69	-2.045	2.165	69.6	75.1	29.5	0.948	105.3
70			72.6	73.2	35.4		110.6
71			86.4	72.1	39.8		115.5
72			71.0	71.3	43.2		120.1
73			82.6	83.0	14.1		97.1
74							
75	-1.715	2.382	36.3	43.4	28.6	0.947	72.9
76			49.5	50.9	33.6		86.9
77			57.9	56.3	37.3		98.1
78			72.9	60.4	40.0		107.4
79			27.6	22.9	14.9		37.8
80							
81	-1.485	2.403	18.5	21.9	13.6	0.949	36.4
82			26.5	29.2	19.1		50.7
83			37.0	35.1	23.7		63.4
84			39.9	39.8	27.6		74.5
85							
86							
87			6.9	6.9	3.4		10.3
88							

	AN	AO	AP	AQ
45	31.5	33.85	16.678	
46	40.7	38.37	22.273	
47	48.0	44.51	29.676	
48	49.5	49.382	37.033	
49	21.4	22.357	12.491	
50				
51	21.4	20.371	6.4	
52	23.3	21.872	9.013	
53	26.7	29.868	14.057	
54	30.1	35.92	21.051	
55	12.4	12.956	5.021	
56				
57	25.8	31.986	9.535	
58	34.0	38.064	12.829	
59	46.7	43.455	16.262	
60	47.9	46.355	21.9	
61	14.5	14.025	6.5	
62				
63	81.6	68.51	29.485	
64	85.4	75.591	32.59	
65	114.9	89.99	40.384	
66	102.2	102.948	46.909	
67	39.1	41.831	26.08	
68				
69	103.1	105.942	32.423	
70	103.5	101.544	42.141	
71	133.9	117.233	45.371	
72	119.5	122.349	48.696	
73	68.4	75.078	16.09	
74				
75	64.2	70.646	29.959	
76	89.1	89.384	35.4	
77	110.5	104.69	40.732	
78	107.5	124.3	48.082	
79	35.4	36.486	21.912	
80				
81	32.7	37.216	15.329	
82	50.5	54.92	20.192	
83	56.6	68.49	28.602	
84	78.6	81.666	35.616	
85	25.4			
86	21.4			
87	16.6	19.629	10.098	
88				

	A	B	C	D	E	F	G	H	I
89	14	1	12 feb 88	14:14	30.5	16.8	0.189	47.8	46.7
90					30.4	19.1	0.329	37.9	47.9
91					30.3	13.4	0.470	52.9	46.5
92					29.8	23.2	0.600	64.1	61.5
93					29.8	23.2	0.020	38.8	40.3
94									
95	2	1	04 dec 88	15:48	49.0	19.0	0.190	76.0	78
96					51.0	19.0	0.320	89.0	87
97					49.0	19.0	0.460	103.0	106
98					49.0	19.0	0.600	111.0	114
99									
100	3	1	18 dec 86		39.0	17.0	0.190	50.0	51.1
101					41.0	17.0	0.320	63.0	64
102					40.0	17.0	0.460	70.0	73.4
103					40.0	17.0	0.600	81.0	85.5
104									
105									
106									

	J	K	L	M	N	O	P	Q	R
89	2	15:29	0.949	10.3		10.8	37.5	nb/.5mb/	5.868
90			9.99	17.1		16.6	20.8	m/m/m	5.868
91				21.9		21.5	31.0		5.868
92			0.951	26.4		27	37.7		5.868
93			10.8	10.9		9.6	27.9		5.868
94			0.9493						
95	###	9999	0.9428	31.1				nb/mb/s	7.011
96			15.2	44.5				m/m/m	7.011
97		9999	0.942	49.7					7.011
98				54.2					7.011
99									
100	2		0.9479	20.5				nb/mb/s	7.011
101			13.5	37.0				m/m/m	7.011
102			0.95	41.0					7.011
103			14.25	43.0					7.011
104									
105									
106									

	S	T	U	V	W	X	Y	Z
89	7.7	6.453	6.21E+05	5.21E-03	0.6	9.7	4.09	-0.462
90	7.7	6.453	1.08E+06	4.61E-03	1.6	15.5	3.81	-0.220
91	7.7	6.453	1.54E+06	4.27E-03	3.0	18.9	3.59	-0.064
92	7.7	6.453	1.97E+06	4.07E-03	4.7	21.7	3.45	0.045
93	7.7	6.453	6.57E+04	9.45E-03	0.0	10.9	6.10	-1.432
94								
95	9.2	8.087	7.46E+05	5.00E-03	0.7	30.4	4.38	-0.562
96	9.2	8.087	1.26E+06	4.46E-03	1.8	42.7	4.06	-0.344
97	9.2	8.087	1.81E+06	4.14E-03	3.5	46.2	3.79	-0.178
98	9.2	8.087	2.35E+06	3.92E-03	5.7	48.5	3.58	-0.063
99								
100	9.2	8.087	7.46E+05	5.00E-03	0.7	19.8	4.29	-0.513
101	9.2	8.087	1.26E+06	4.46E-03	1.8	35.2	4.06	-0.297
102	9.2	8.087	1.81E+06	4.14E-03	3.5	37.5	3.79	-0.134
103	9.2	8.087	2.35E+06	3.92E-03	5.7	37.3	3.55	-0.019
104								
105								
106								

	AA	AB	AC	AD	AE	AF
89	-1.277	3.511	9.9	37.3	4.68	-1.348
90			14.8	21.5	3.96	-1.135
91			19.0	30.8	3.80	-0.903
92			22.1	37.3	3.68	-0.916
93			1.9	36.9	6.63	-2.393
94						
95	-1.583	3.498	31.1	44.2	4.54	-1.374
96			41.5	45.7	4.09	-1.147
97			44.9	54.6	3.87	-0.990
98			50.1	55.1	3.64	-0.874
99						
100	-1.479	3.567	21.5	27.7	4.44	-1.348
101			30.8	30.3	4.00	-1.122
102			35.7	30.8	3.70	-0.964
103			41.0	34.3	3.52	-0.849
104						
105						
106						

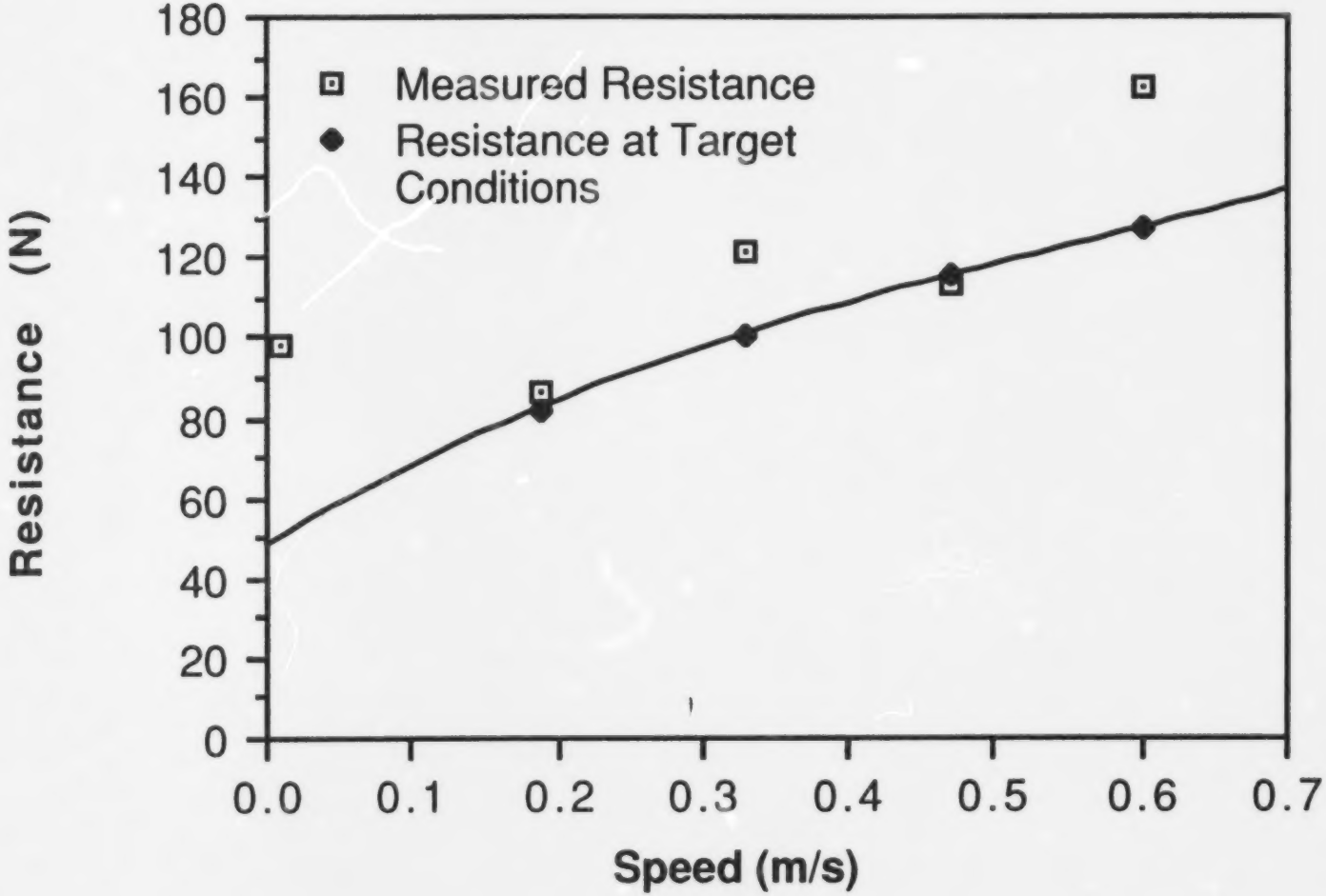
	AG	AH	AI	AJ	AK	AL	AM
89	-1.998	1.881	29.5	33.7	9.7	0.948	43.9
90			33.5	33.7	14.4		49.8
91			23.4	33.7	18.7		55.5
92			39.9	33.7	22.3		60.8
93			39.6	33.5	1.9		35.4
94							
95	-1.777	2.085	42.6	43.5	32.5	0.9419	76.7
96			49.8	48.9	40.3	14.85	91.1
97			51.9	53.0	46.9		103.5
98			55.1	56.3	52.4		114.4
99							
100	-1.851	1.933	27.3	31.0	22.5	0.9466	54.2
101			31.0	33.5	29.5	13	64.9
102			31.9	35.3	35.7		74.6
103			33.2	36.8	41.0		83.5
104							
105							
106							

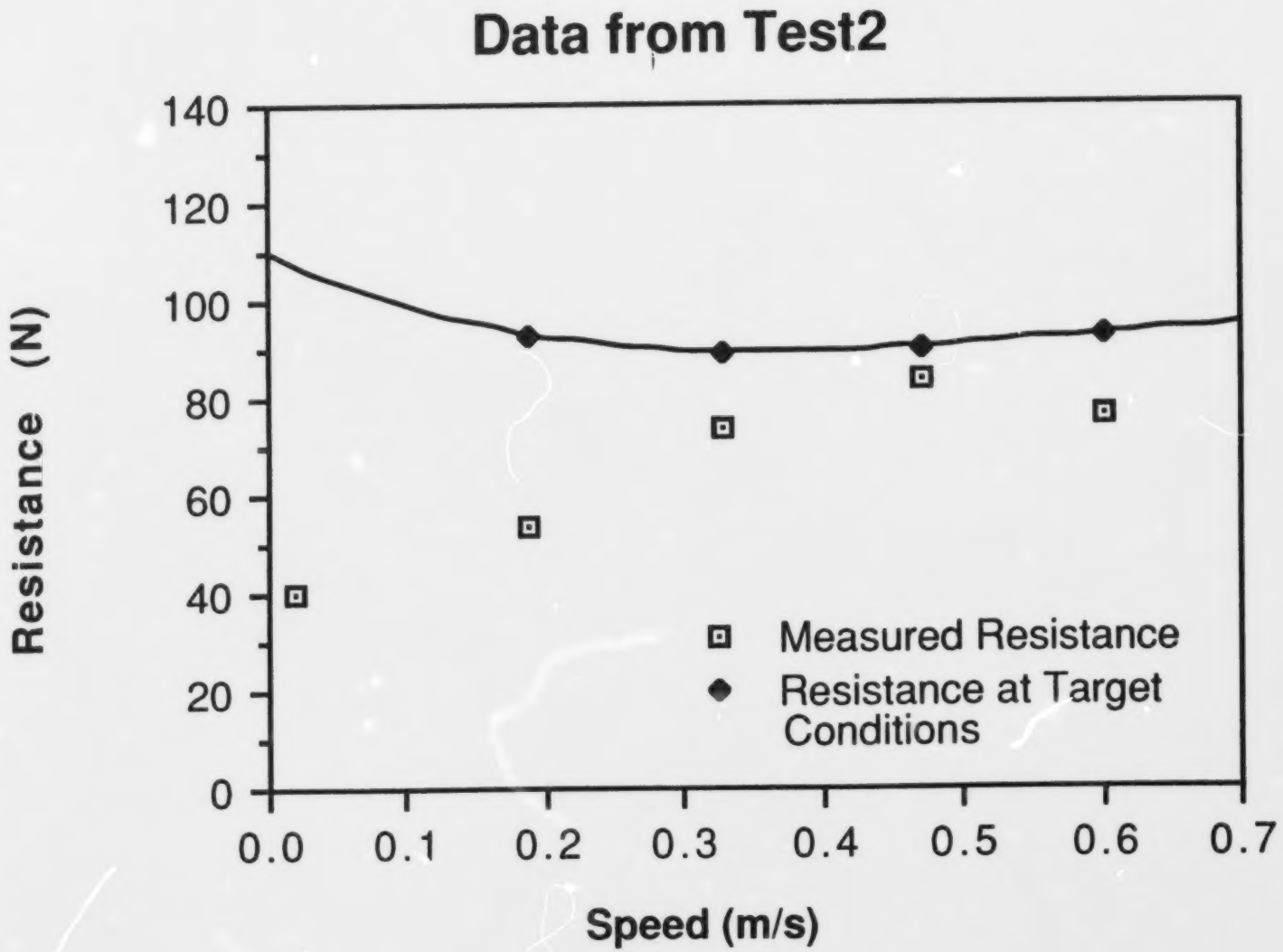
	AN	AO	AP	AQ
89	47.8	37.67	9.927	
90	37.9	50.4	16.573	
91	52.9	49.95	21.569	
92	64.1	58.304	26.603	
93	38.8	20.33	11.113	
94				
95	76.0			
96	89.0			
97	103.0			
98	111.0			
99				
100	50.0			
101	63.0			
102	70.0			
103	81.0			
104				
105				
106				

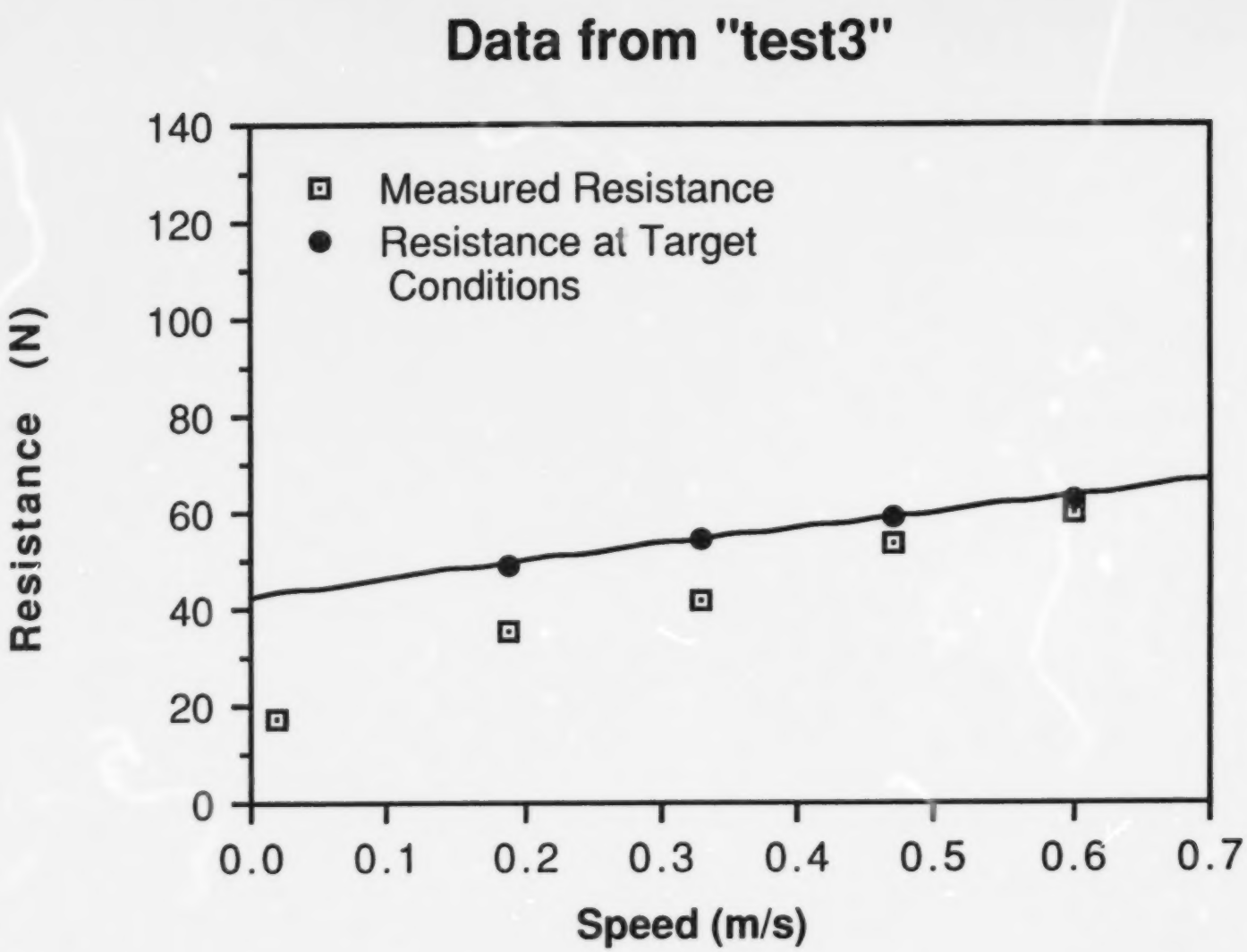
APPENDIX B

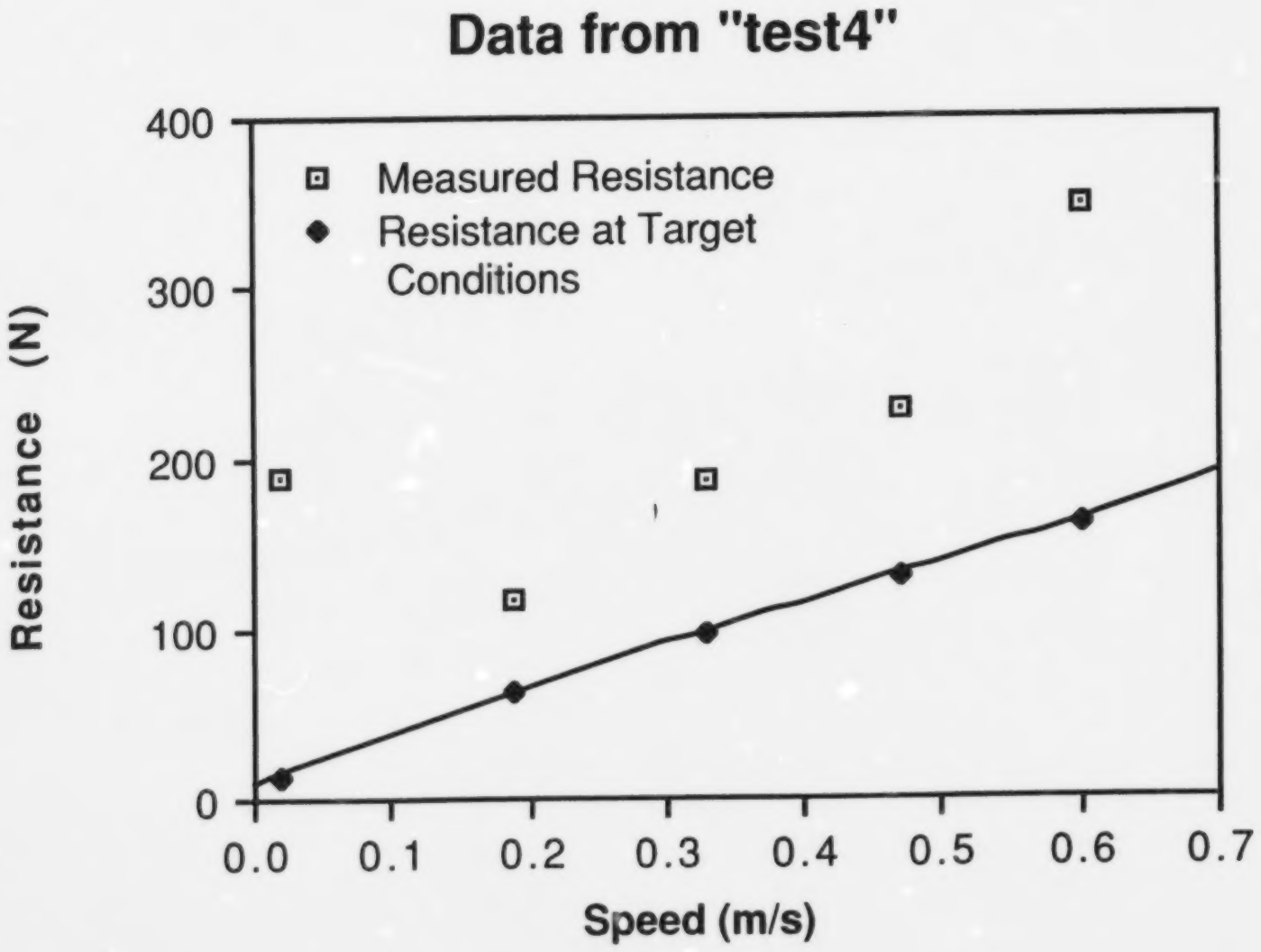
Graphed Data

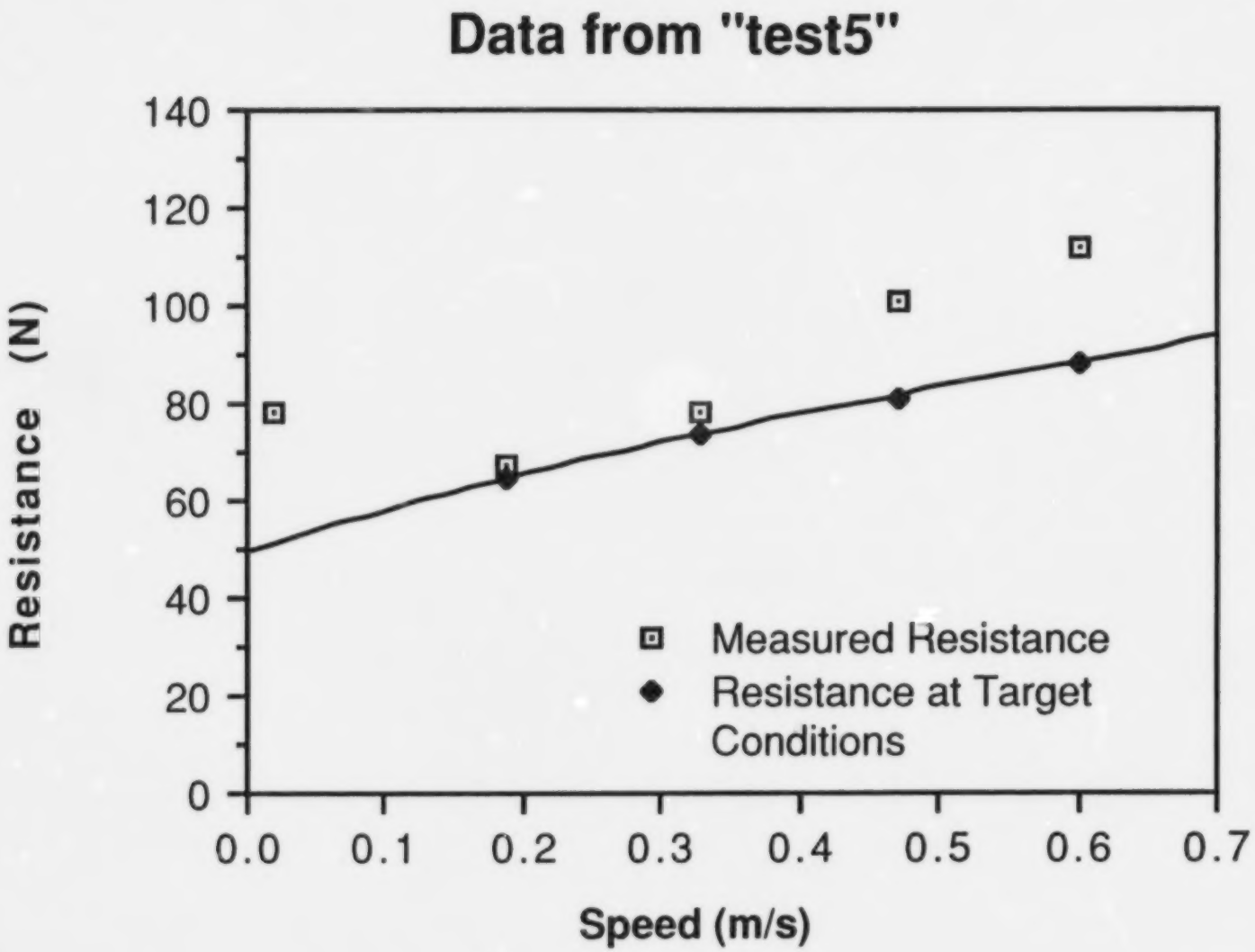
Data from Test1

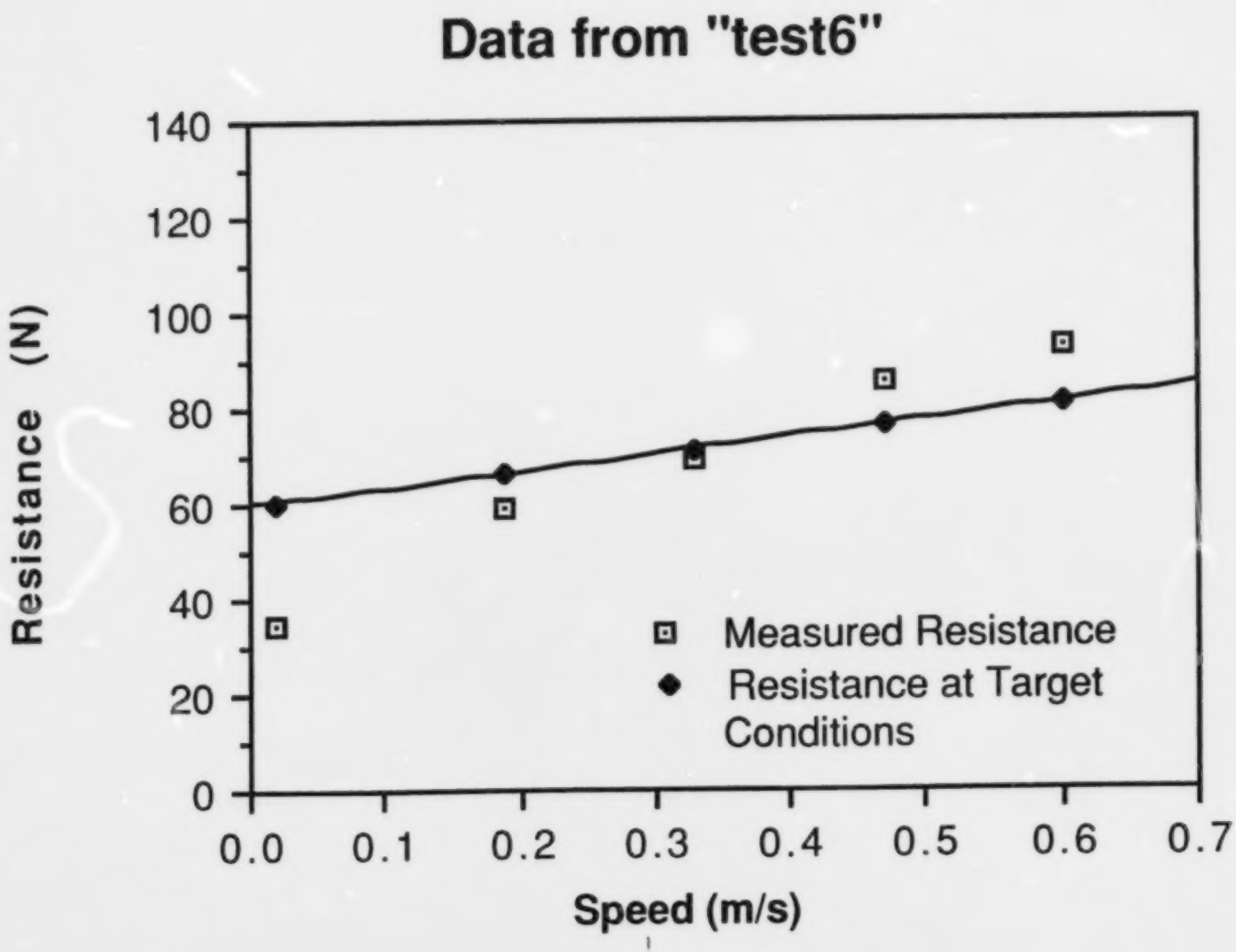


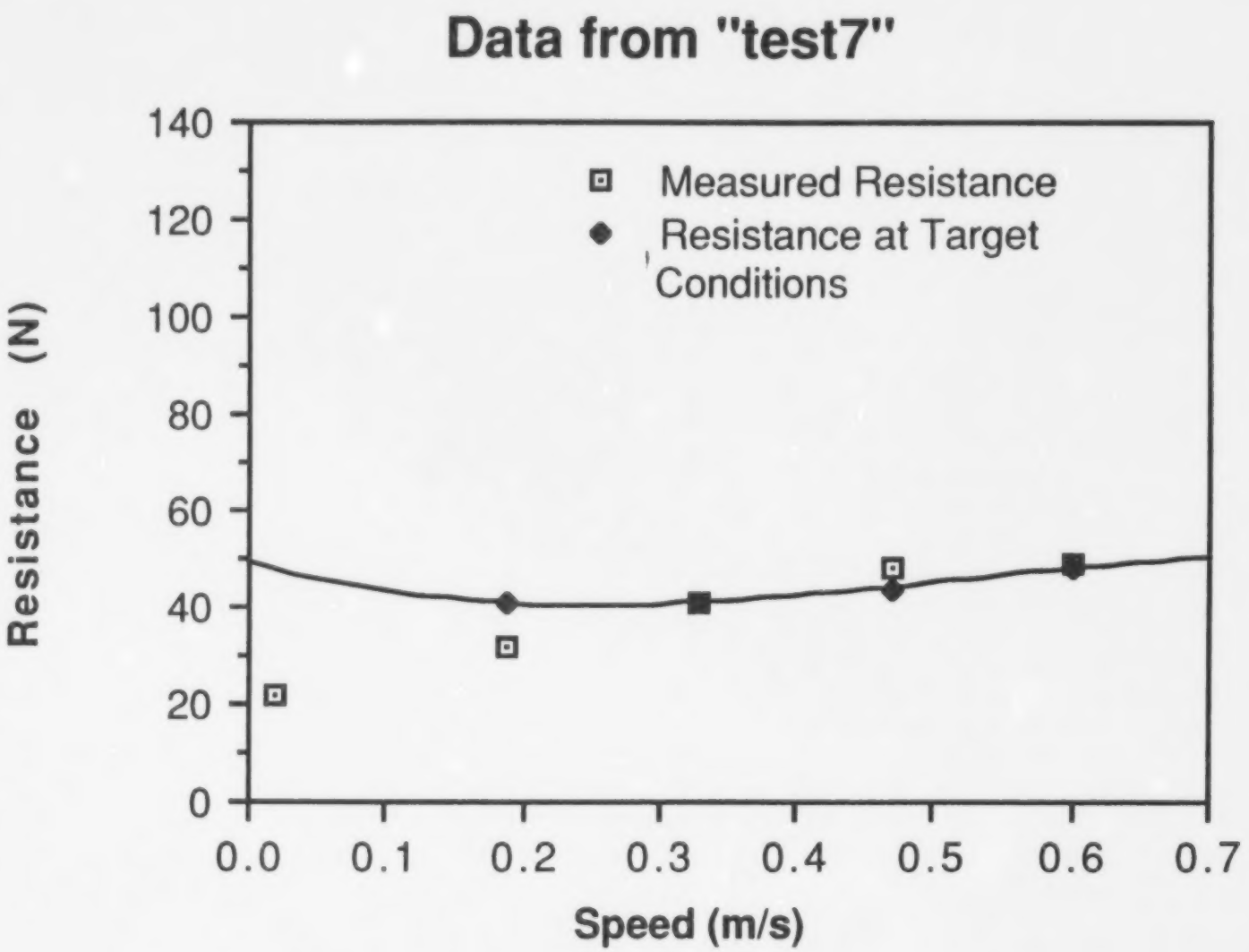

Data from Test2
Resistance (N)
140
120
100
80
60
40
20
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Speed (m/s)
Measured Resistance
Resistance at Target Conditions


Data from "test3"
Measured Resistance
Resistance at Target Conditions
Resistance (N)
Speed (m/s)
0
20
40
60
80
100
120
140
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

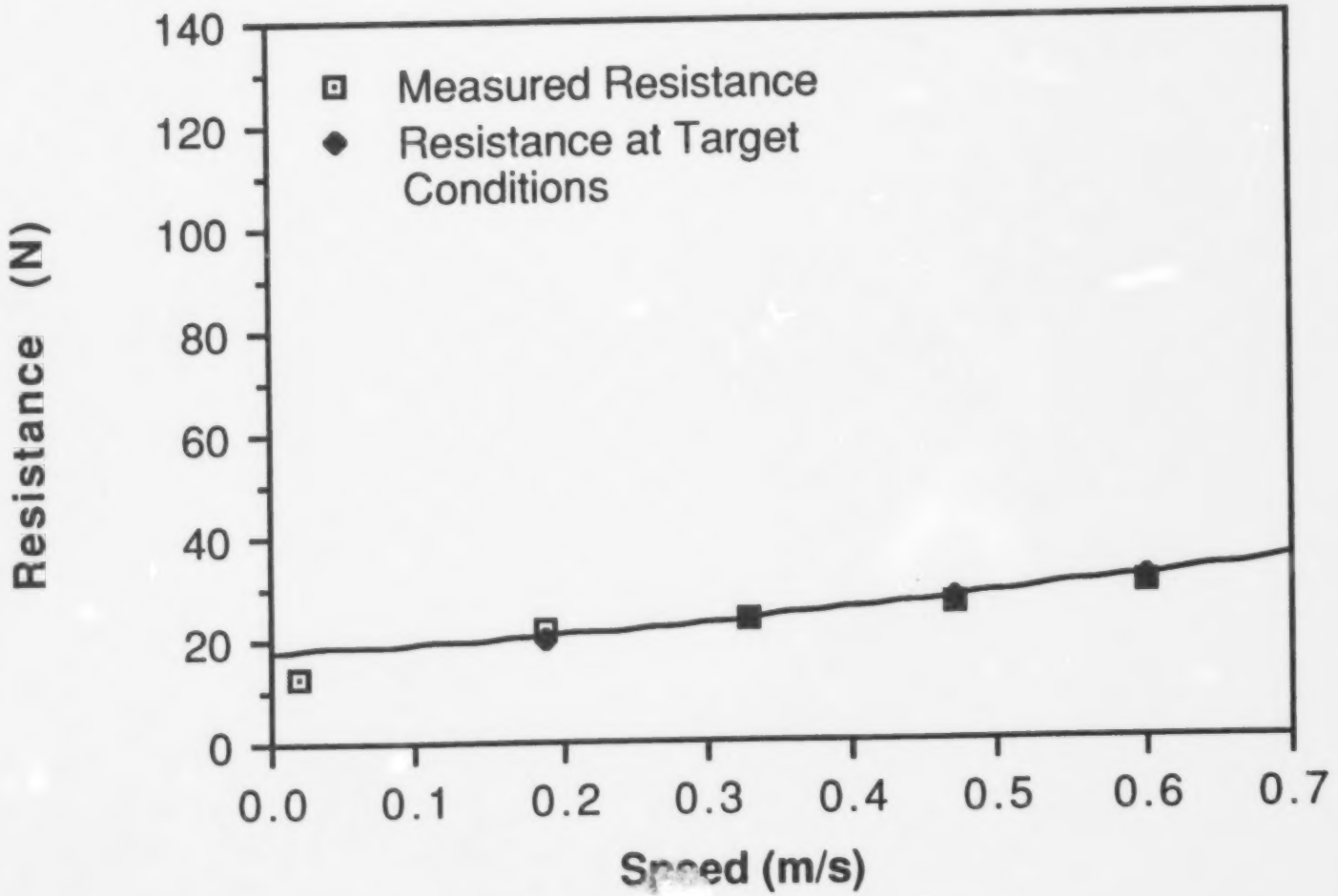

Data from "test4"
Measured Resistance
Resistance at Target Conditions
Resistance (N)
400
300
200
100
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Speed (m/s)


Data from "test5"
Resistance (N)
140
120
100
80
60
40
20
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Speed (m/s)
Measured Resistance
Resistance at Target Conditions

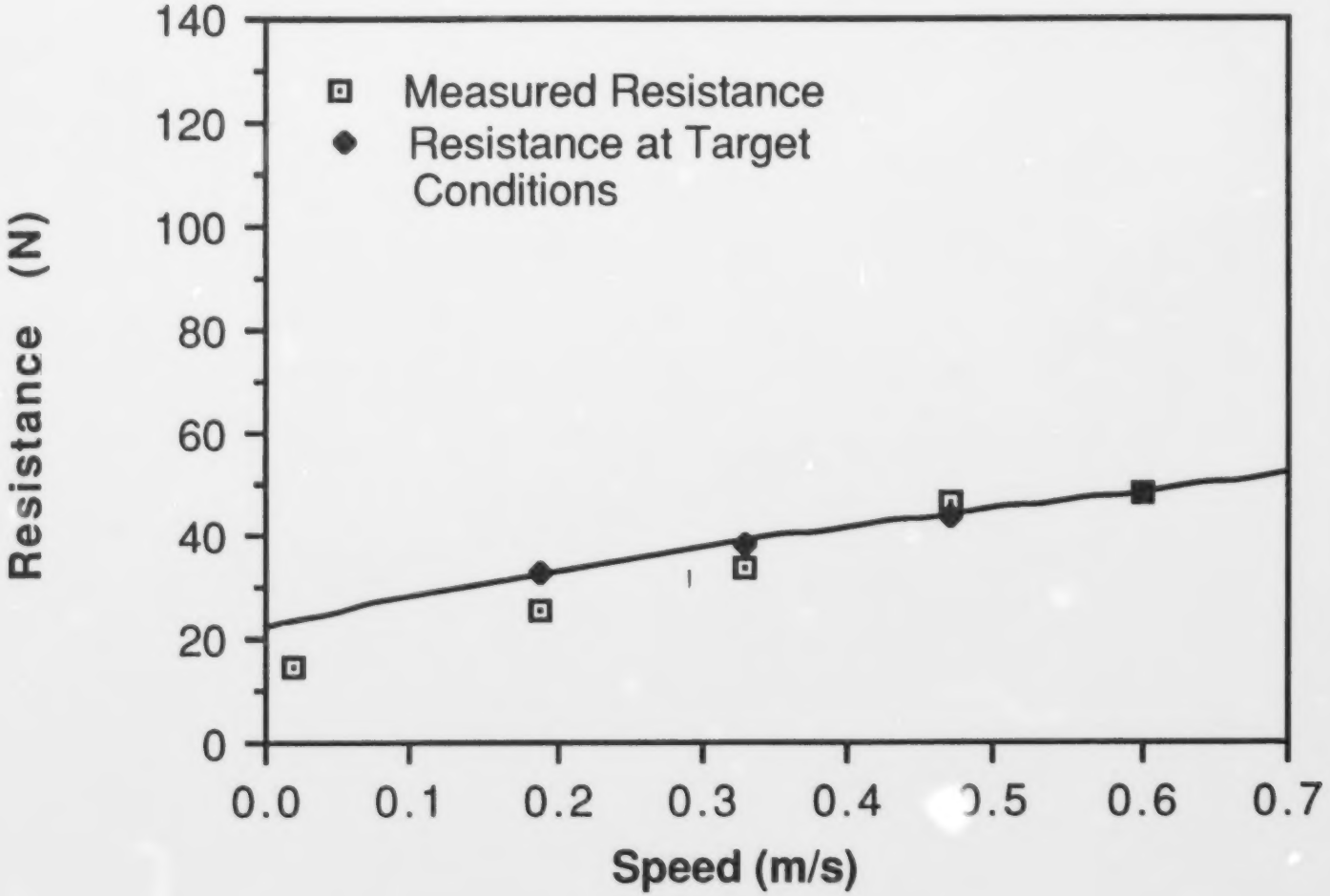

Data from "test6"
Resistance (N)
140
120
100
80
60
40
20
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Speed (m/s)
Measured Resistance
Resistance at Target Conditions

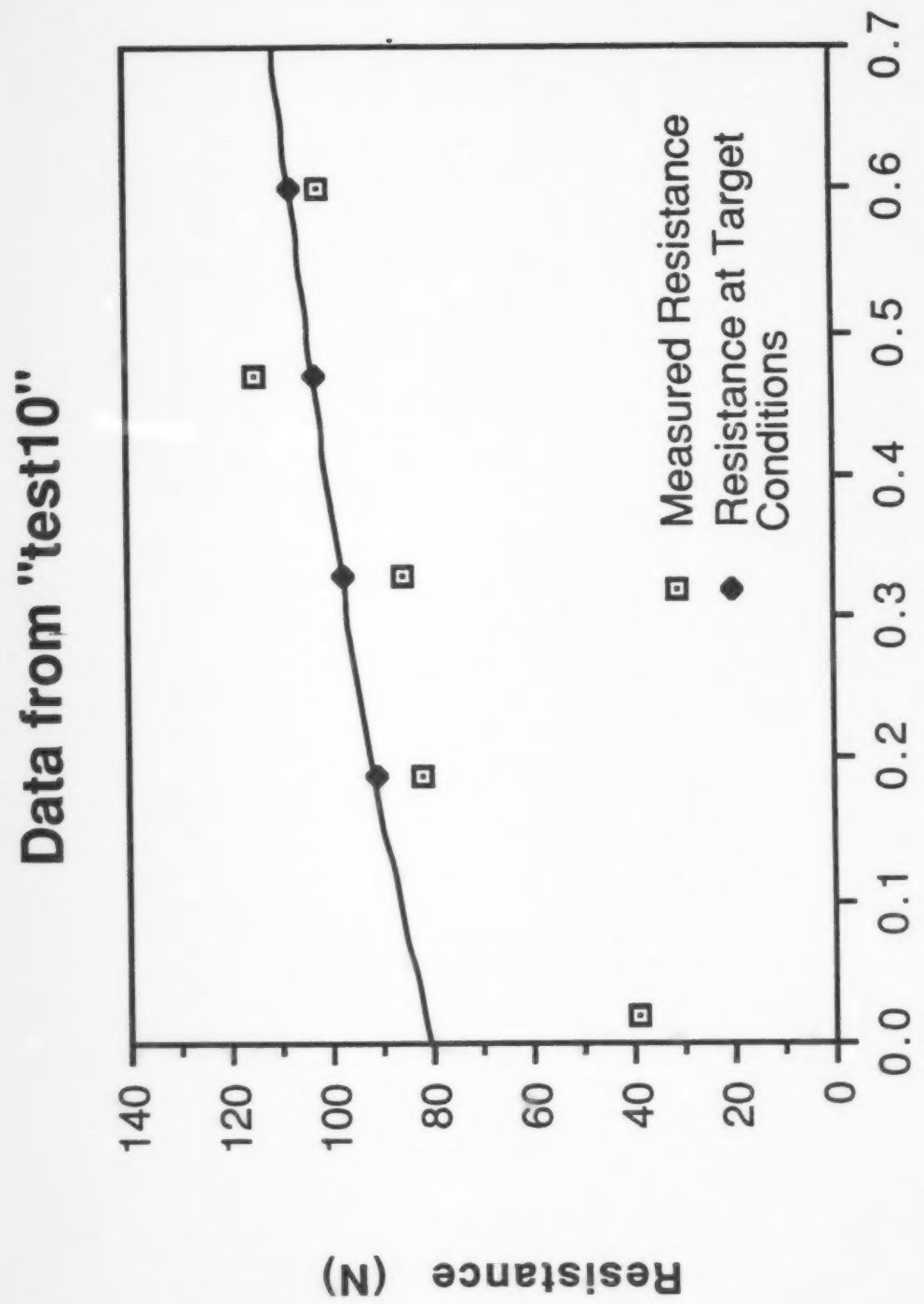

Data from "test7"
Measured Resistance
Resistance at Target Conditions
Resistance (N)
Speed (m/s)
140
120
100
80
60
40
20
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

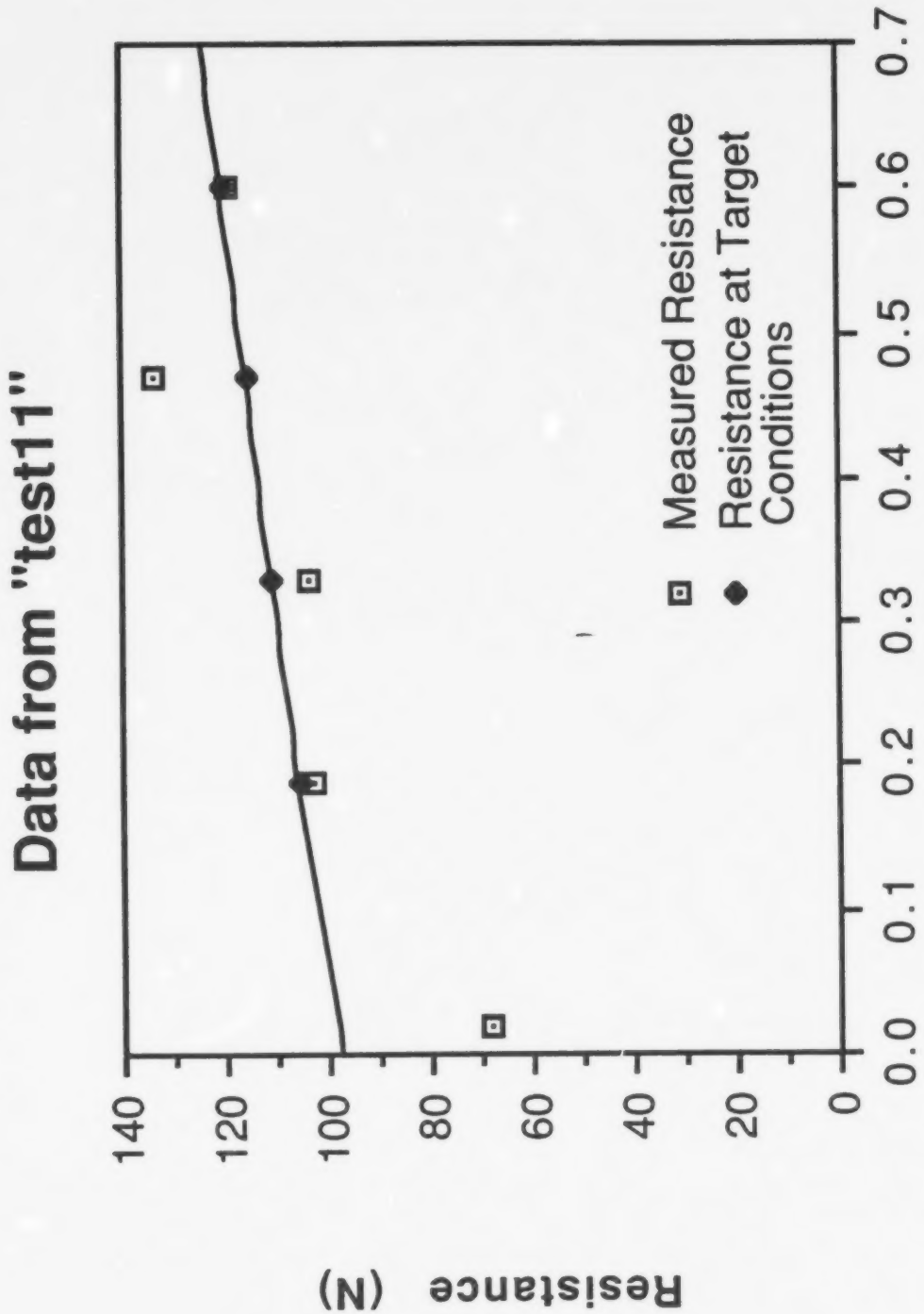
Data from "test8"

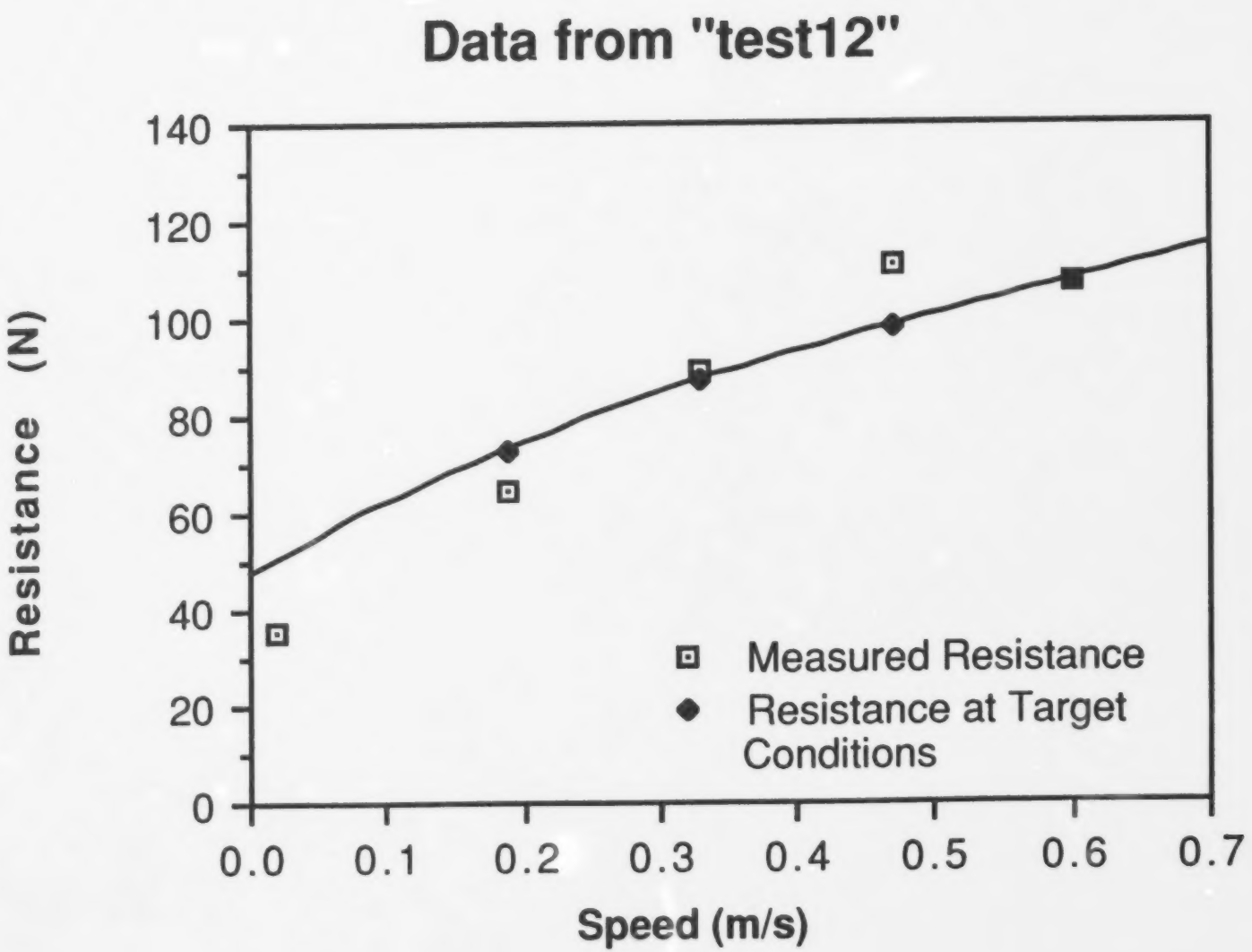


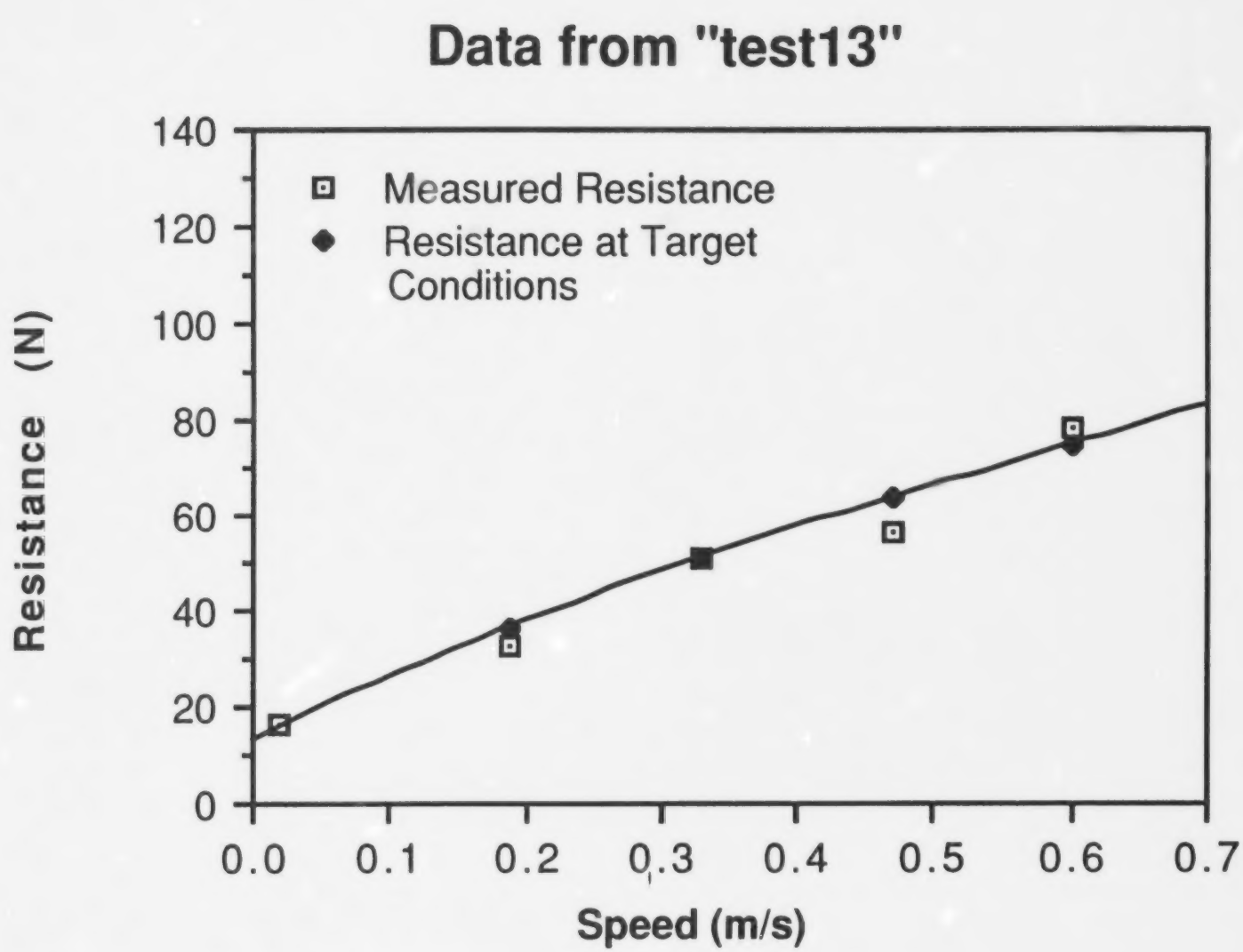
Data from "test9"

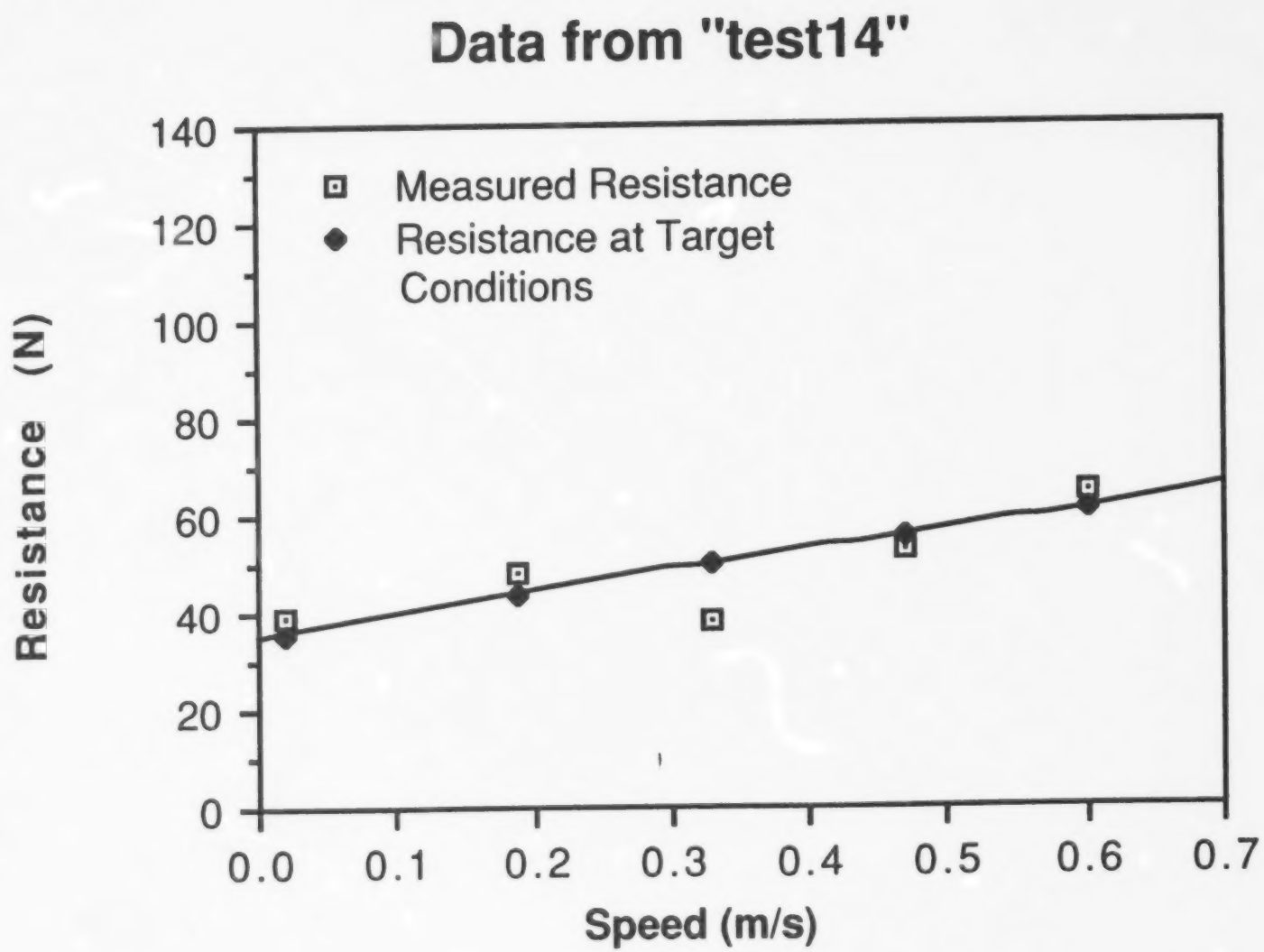



Data from "test10"
Resistance (N)
140
120
100
80
60
40
20
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Speed (m/s)
Measured Resistance
Resistance at Target Conditions

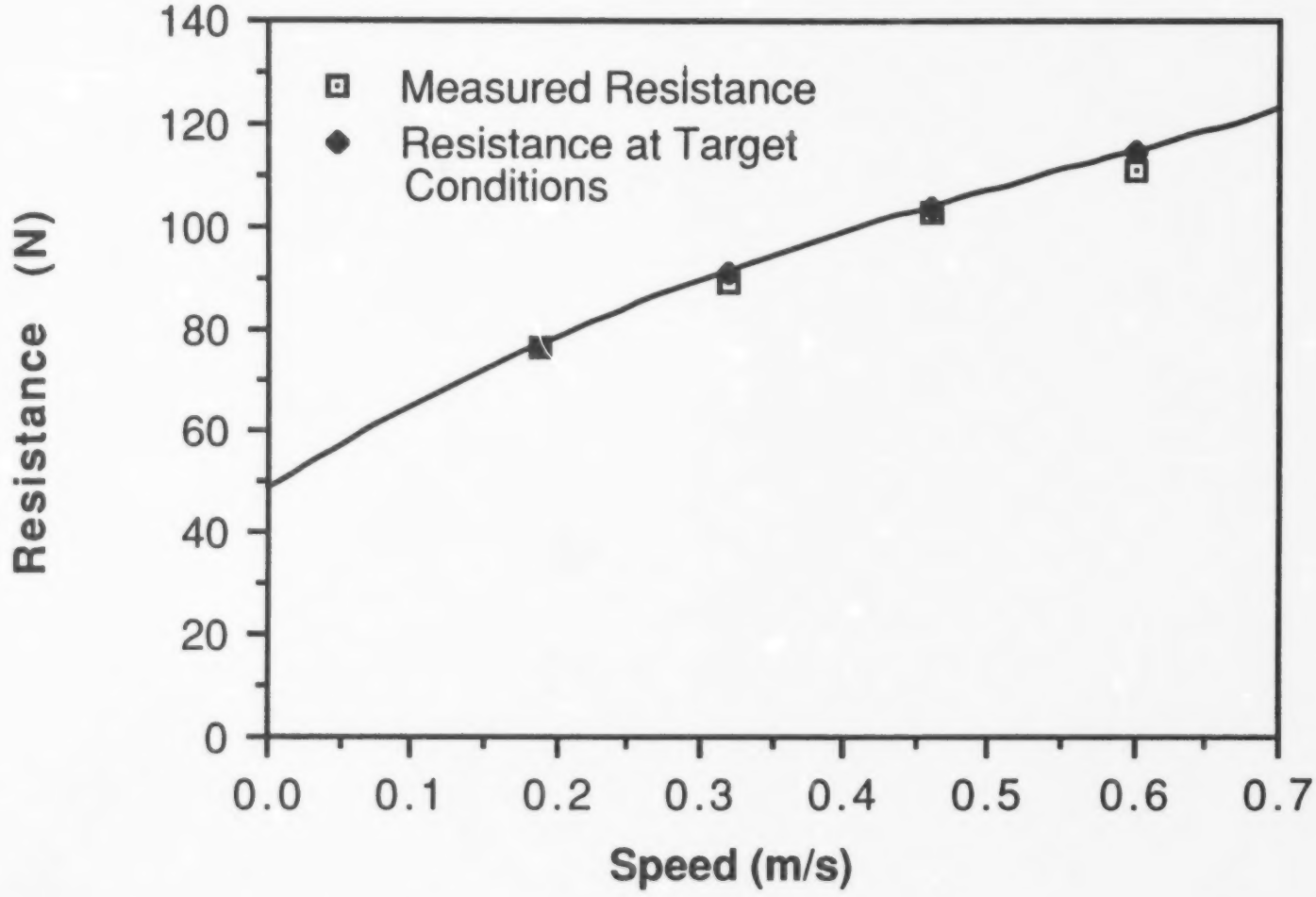

Data from "test11"
Resistance (N)
140
120
100
80
60
40
20
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Speed (m/s)
Measured Resistance
Resistance at Target Conditions


Data from "test12"
Resistance (N)
140
120
100
80
60
40
20
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Speed (m/s)
Measured Resistance
Resistance at Target Conditions

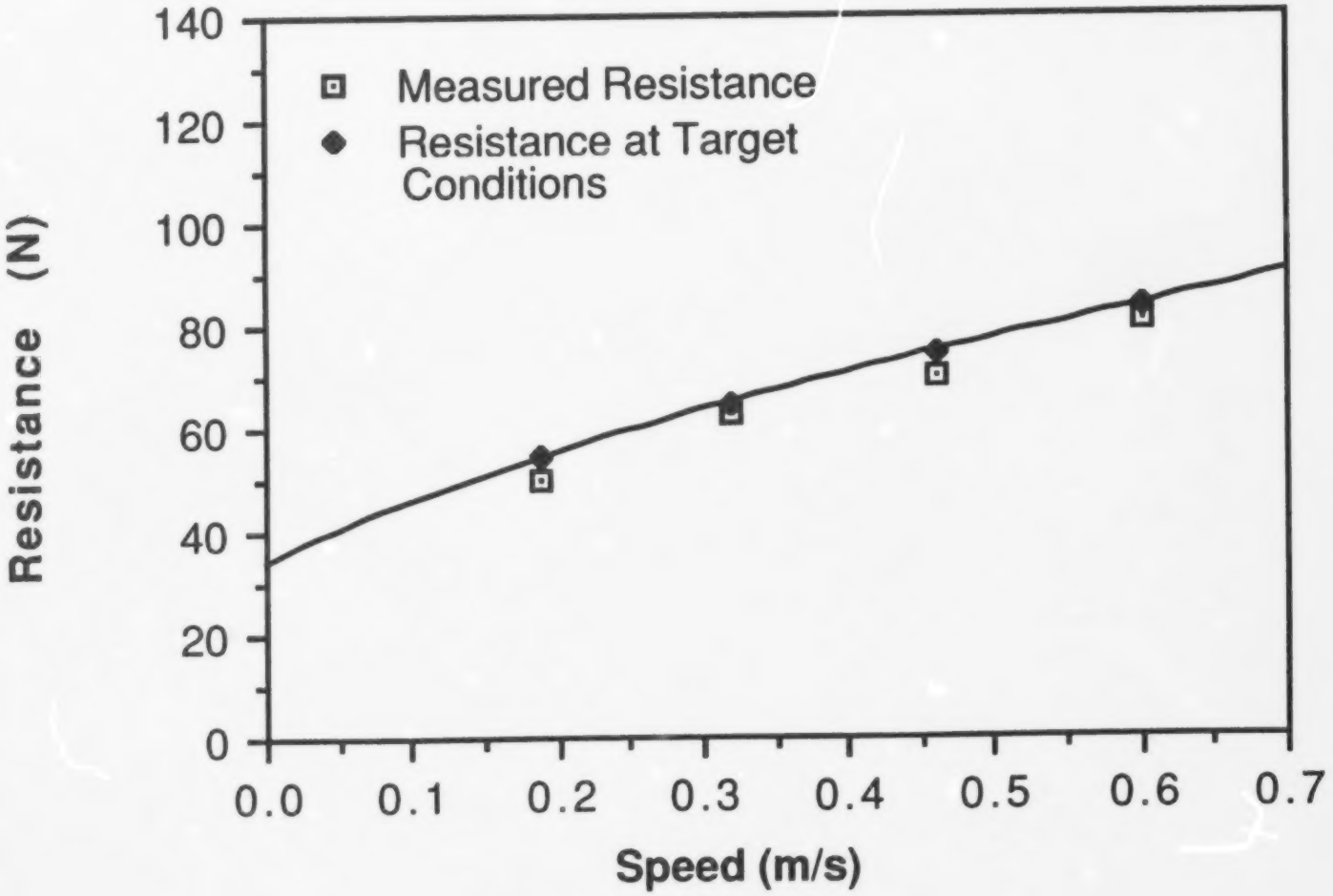

Data from "test13"
Measured Resistance
Resistance at Target Conditions
Resistance (N)
Speed (m/s)
0
20
40
60
80
100
120
140
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7


Data from "test14"
Measured Resistance
Resistance at Target Conditions
Resistance (N)
Speed (m/s)
140
120
100
80
60
40
20
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

Data from friction program, Test 2



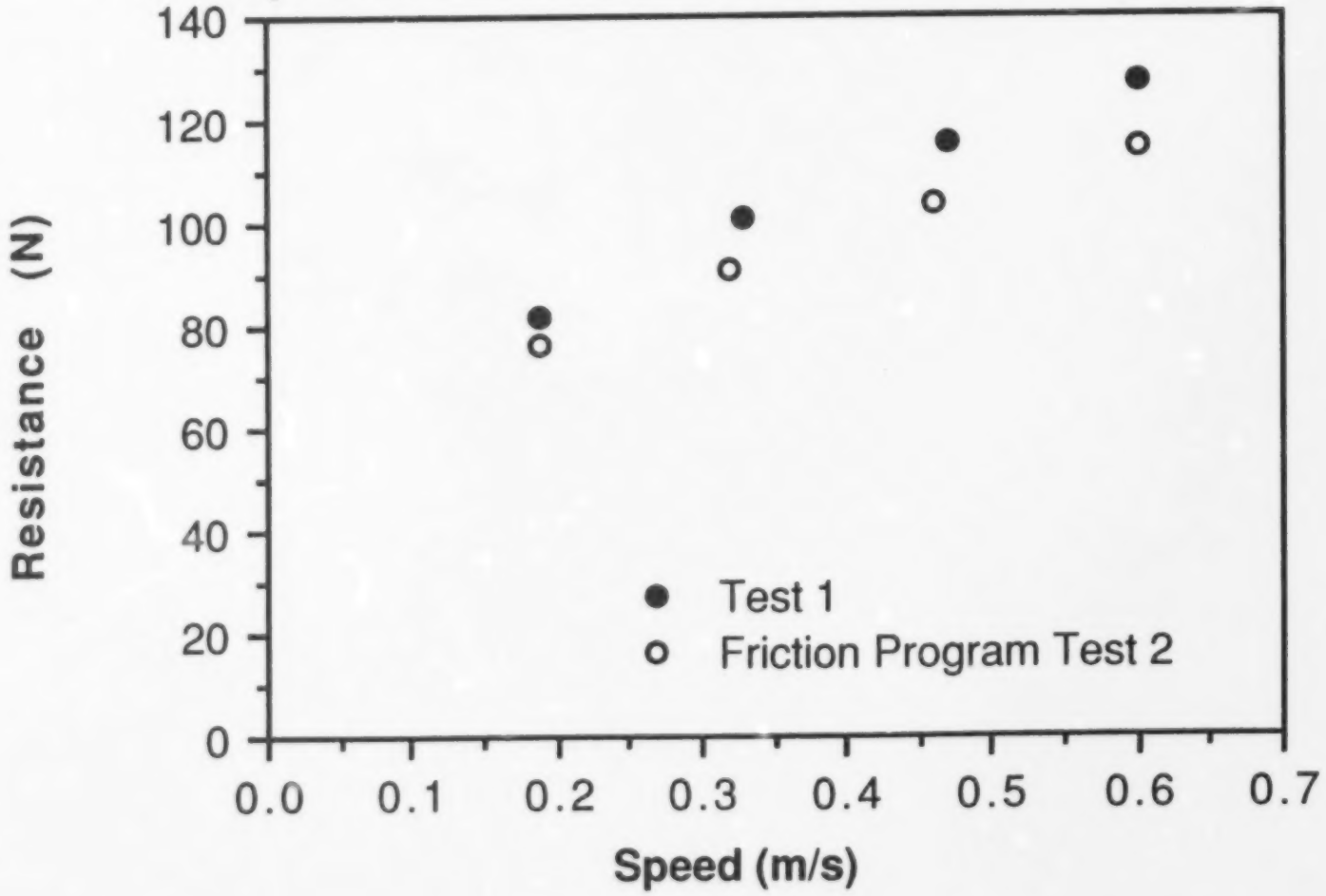
Data from Friction Program, Test 3



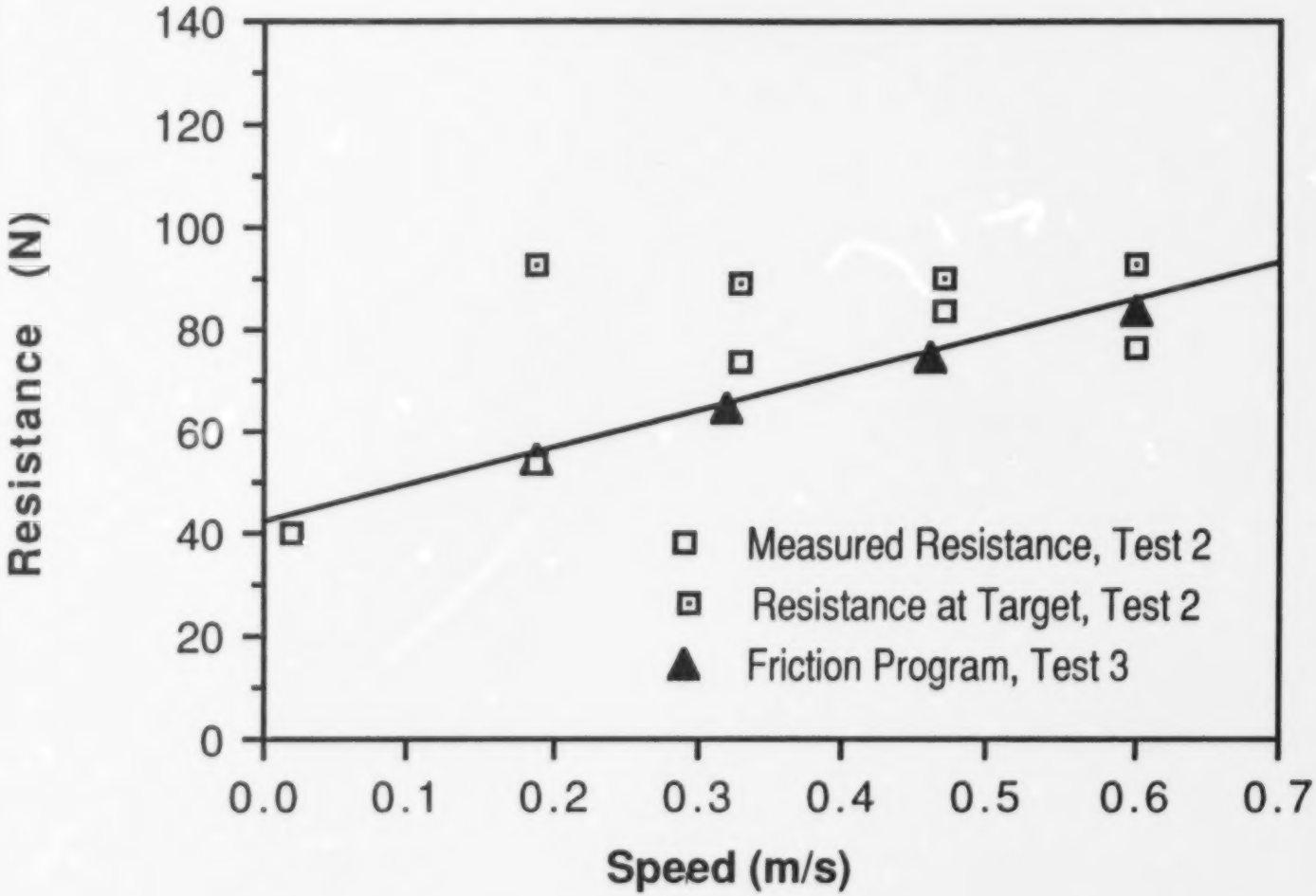
APPENDIX C

Comparison Graphs

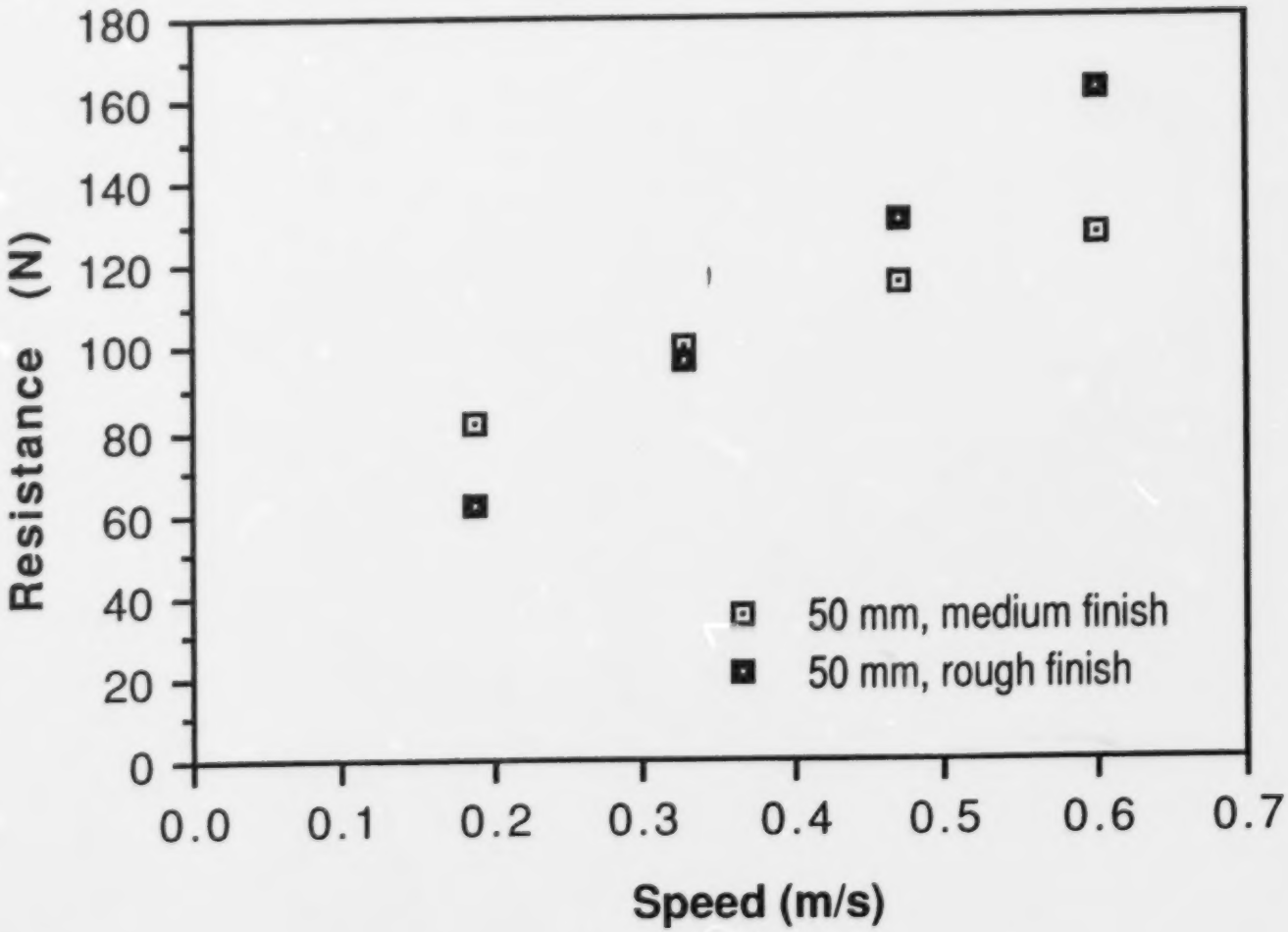
Comparison of 50 mm Ice Sheets.



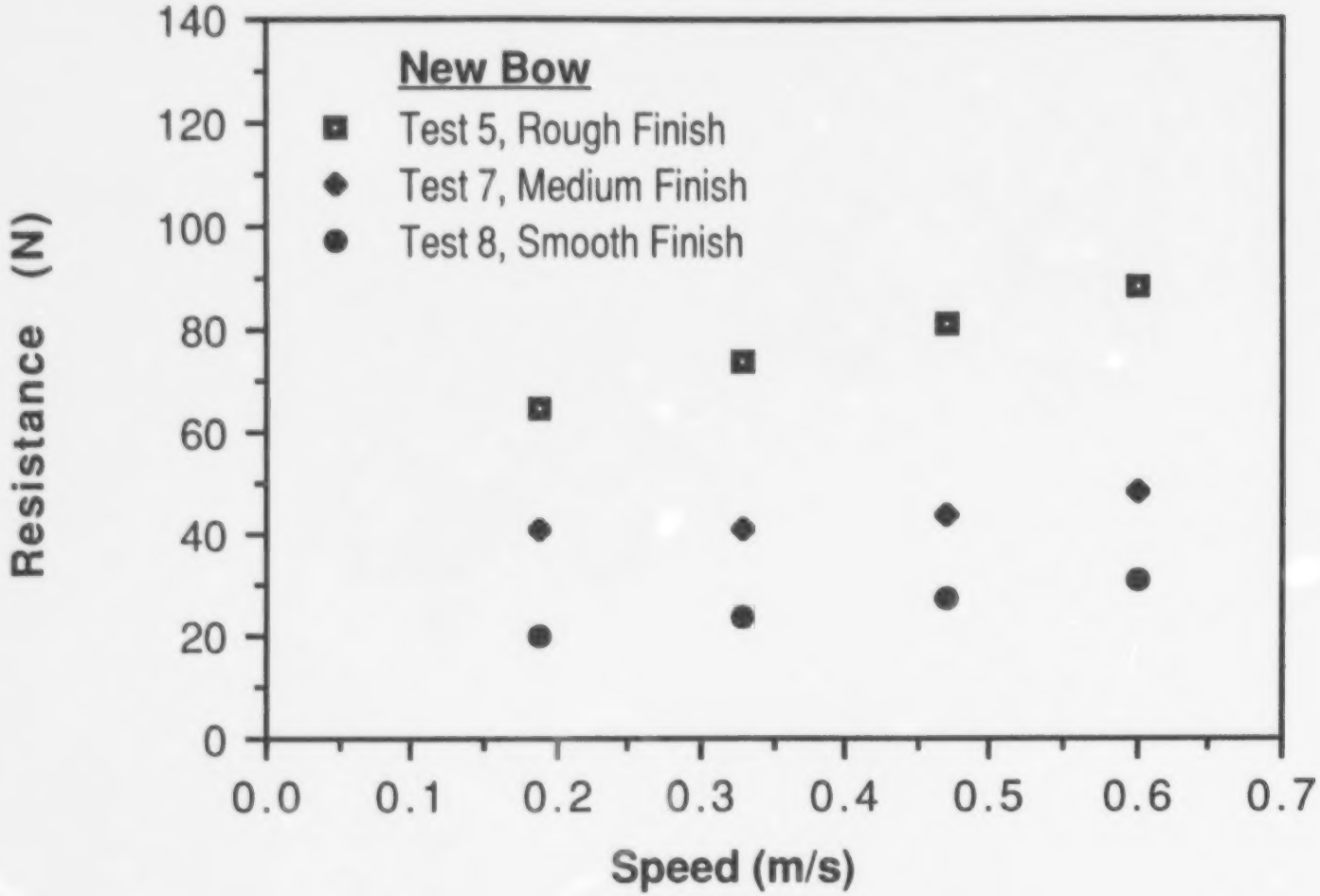
Comparison of 40 mm Ice Sheets



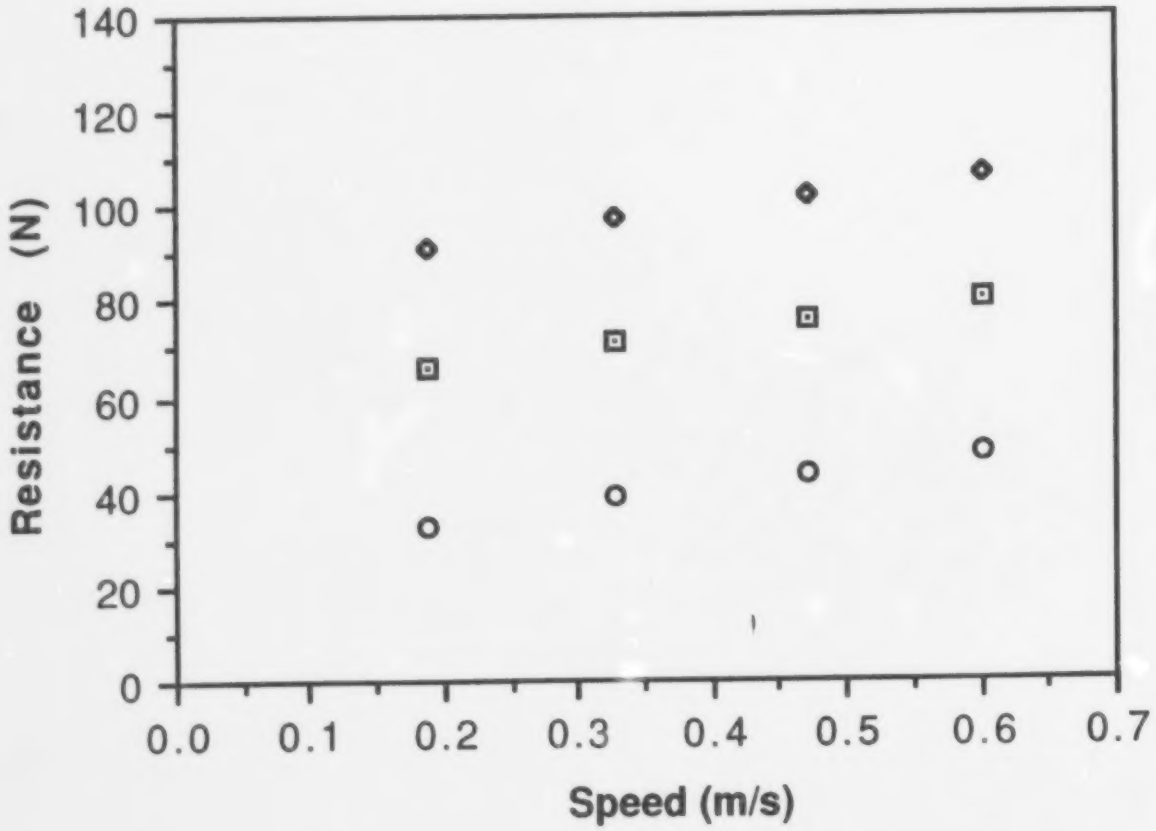
Medium and Rough Finish Models.



Three Surface Finishes on Short Models



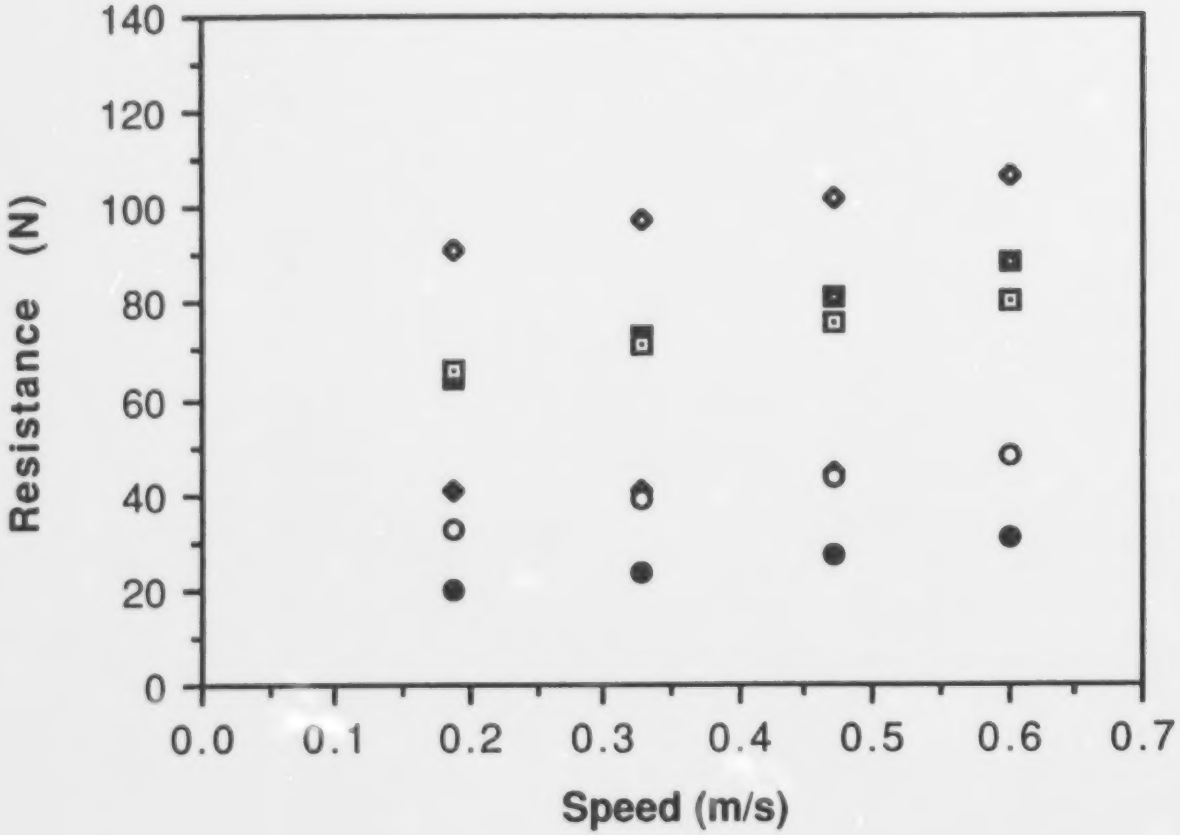
Three Surface Finishes on Short Models



Old Bow

- Test 6, Rough Finish
- Test 10, Medium Finish
- Test 9, Smooth Finish

Three Surface Finishes on Short Models



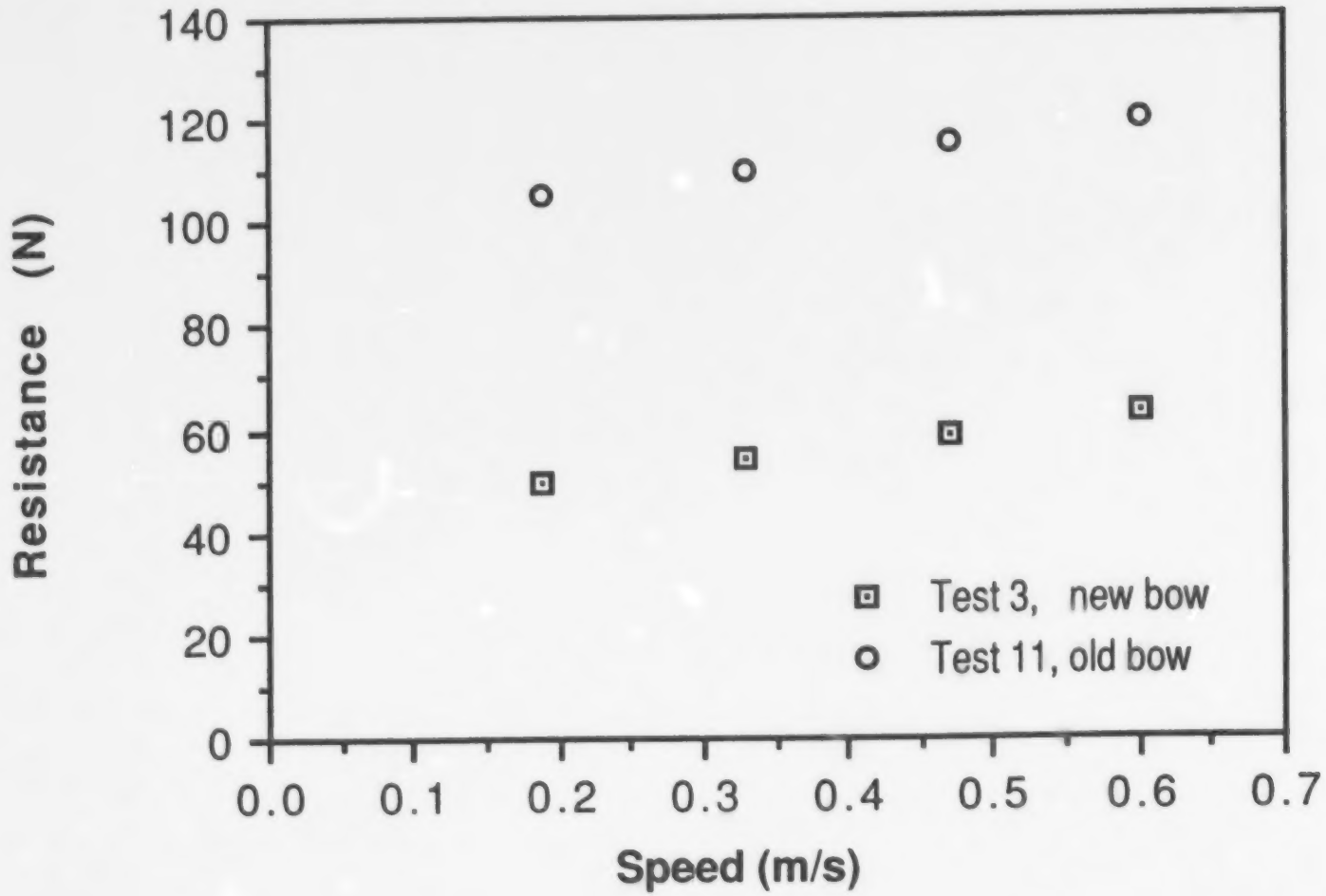
New Bow

- Test 5, Rough Finish
- Test 7, Medium Finish
- Test 8, Smooth Finish

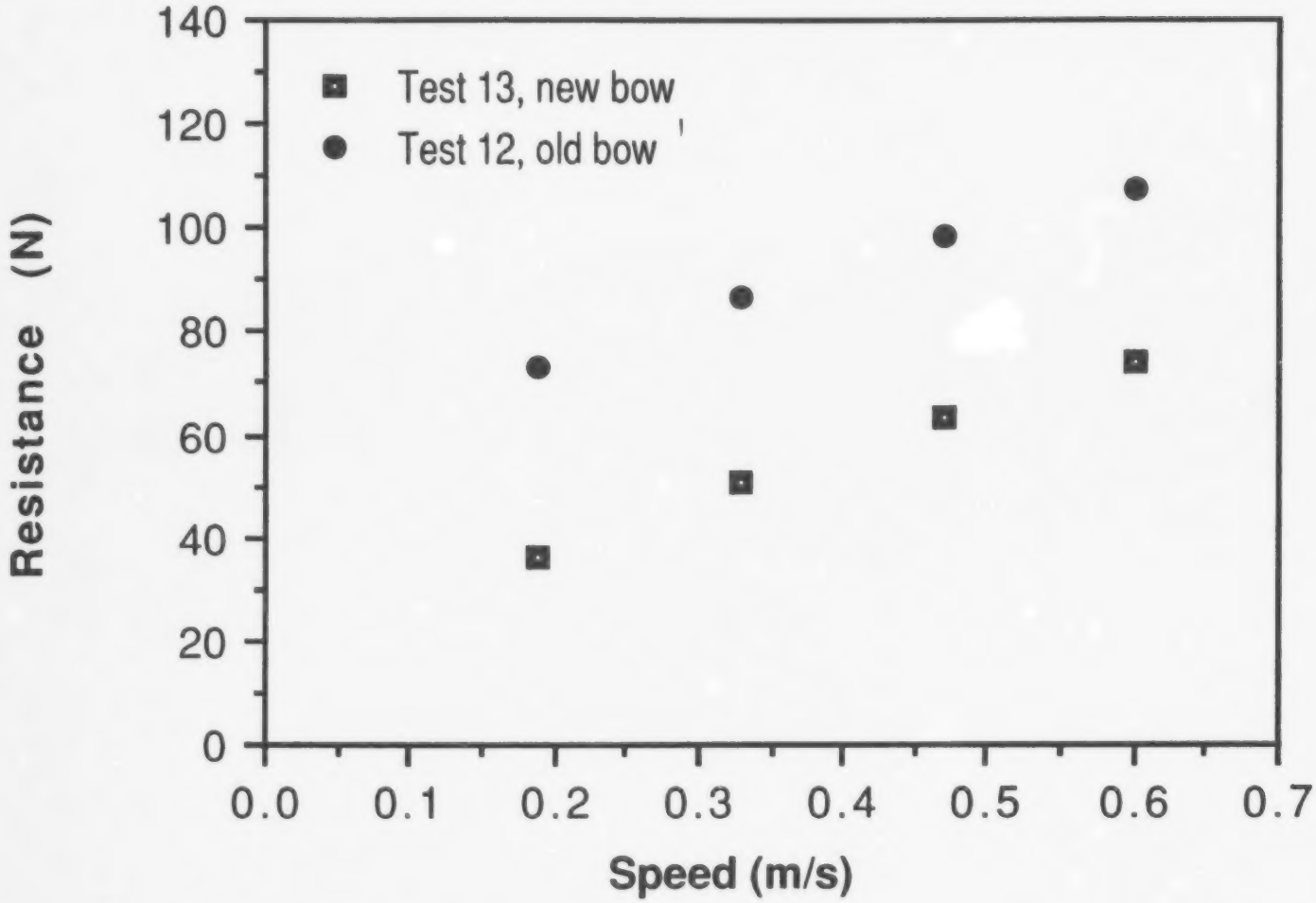
Old Bow

- Test 6, Rough Finish
- Test 10, Medium Finish
- Test 9, Smooth Finish

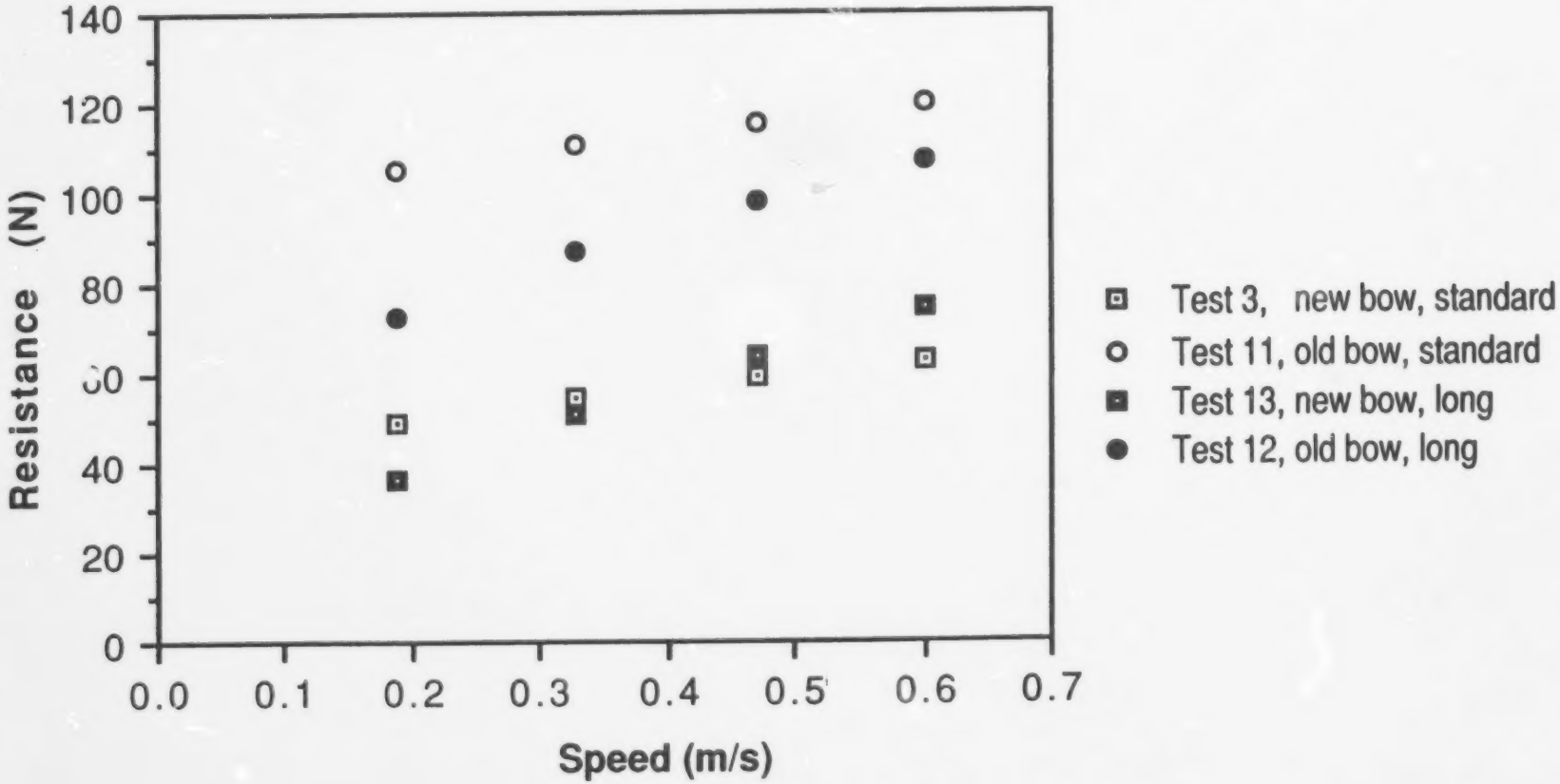
Bow Comparison, Standard Models



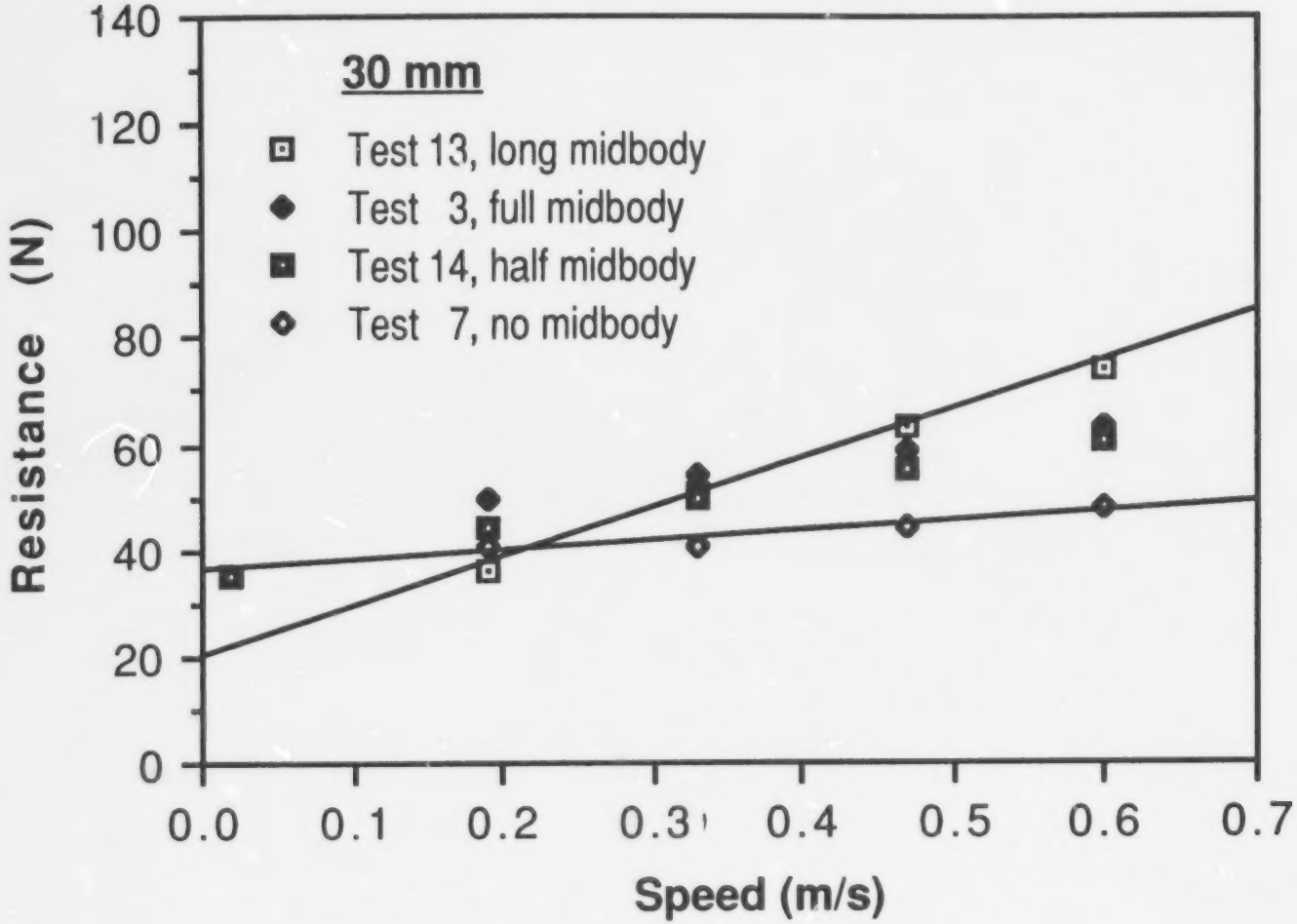
Bow Comparison, Long Model



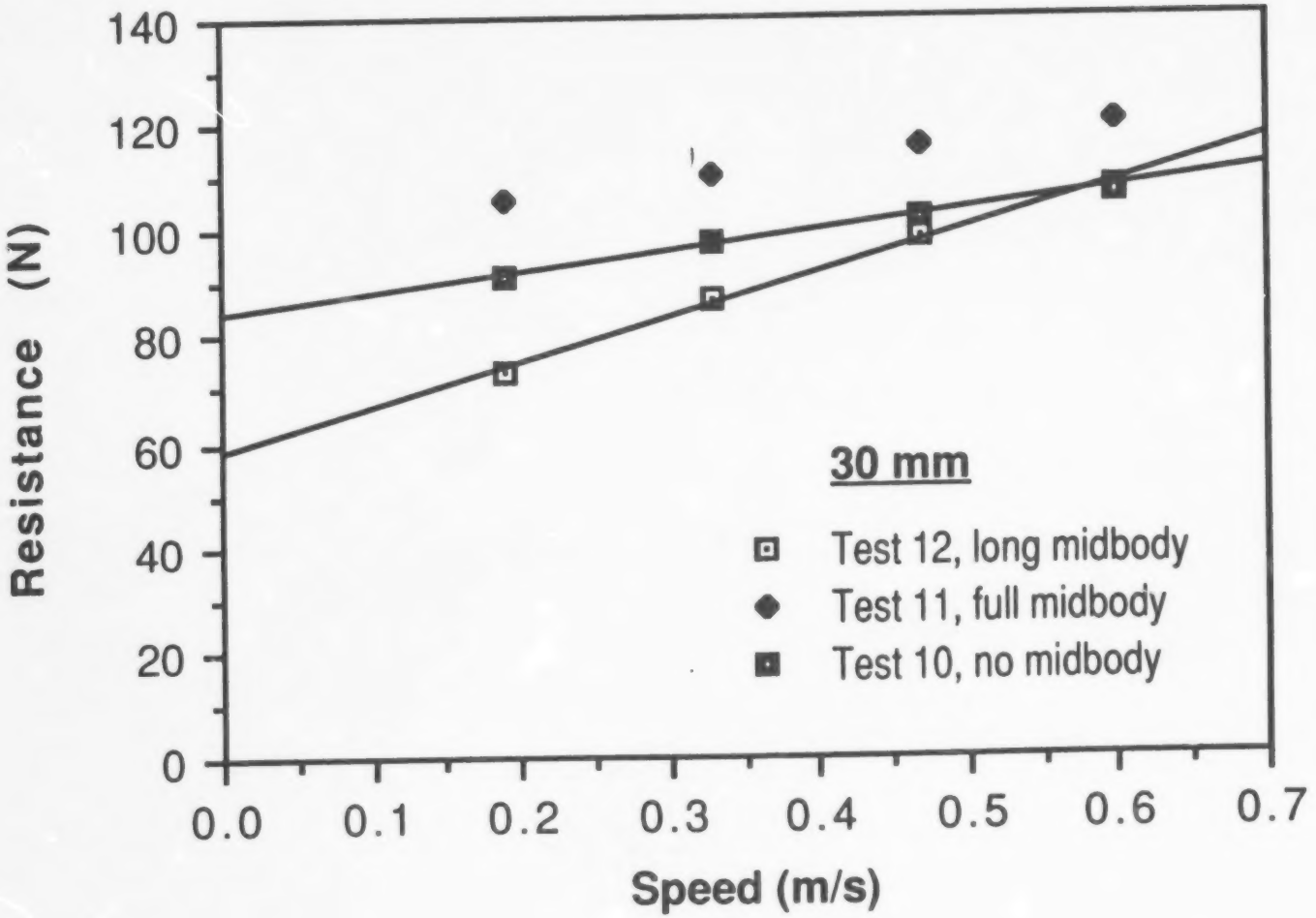
Bow Comparison, Standard & Long Models

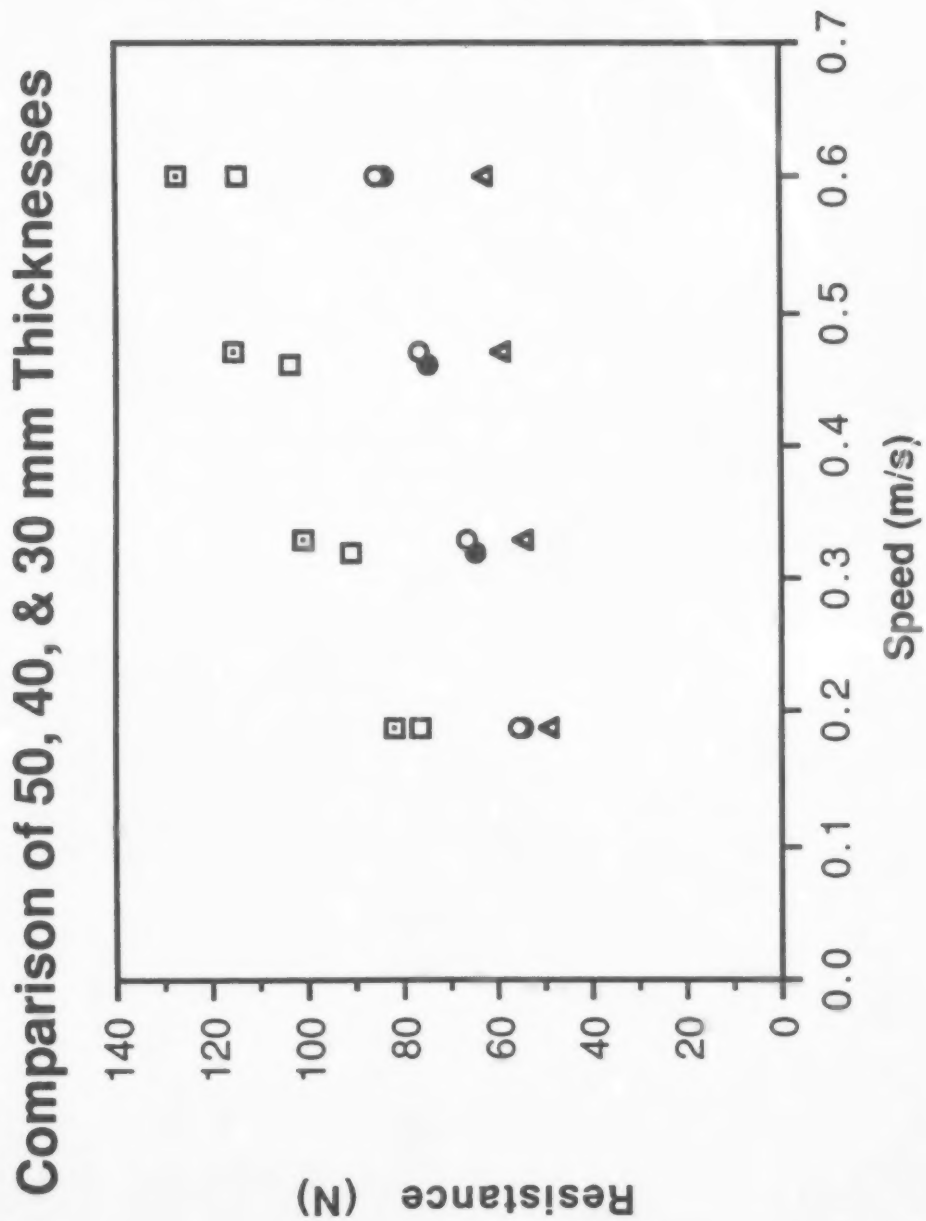


Length Variation for New Bow Models



Length Variation for Old Bow Models




Comparison of 50, 40, & 30 mm Thicknesses
Resistance (N)
140
120
100
80
60
40
20
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Speed (m/s)
Test 1, 50 mm
Test F2, 50 mm
Test 2, 40 mm
Test F3, 40 mm
Test 3, 30 mm

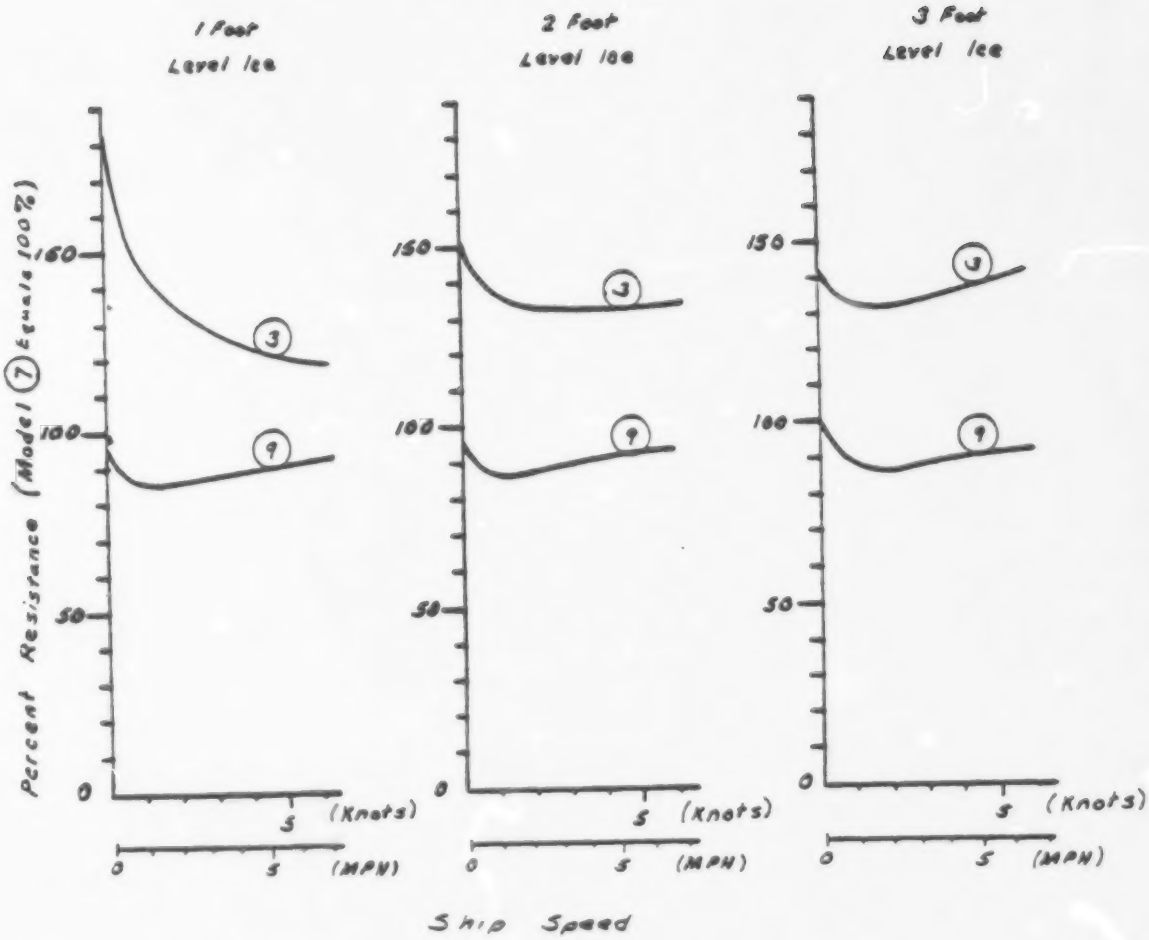
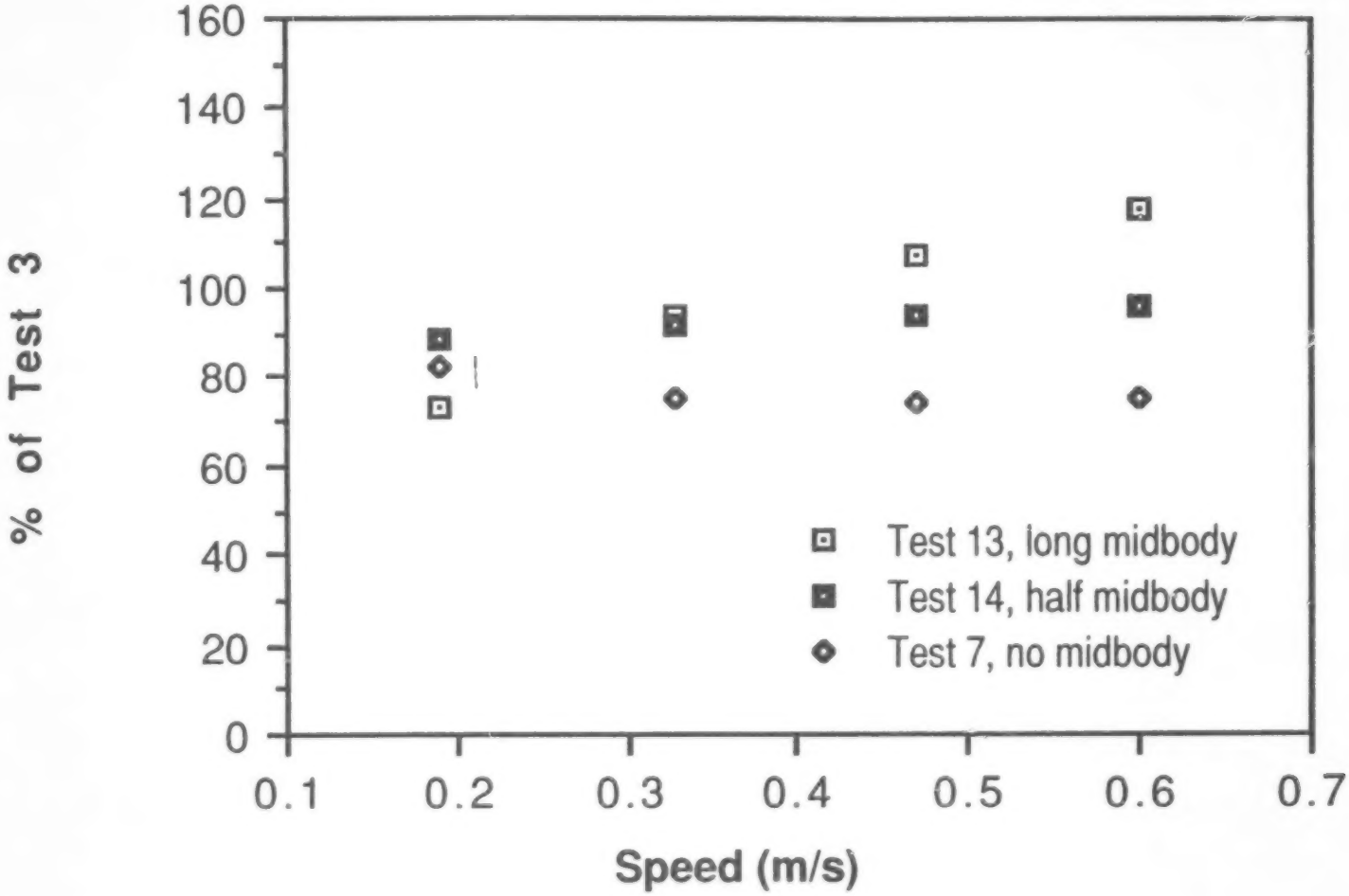


Figure 3.5 Comparison of Level Ice Resistance for Length Variation Series

(Reproduced from Reference 5)

Length Variation in Percent. (New Bow)



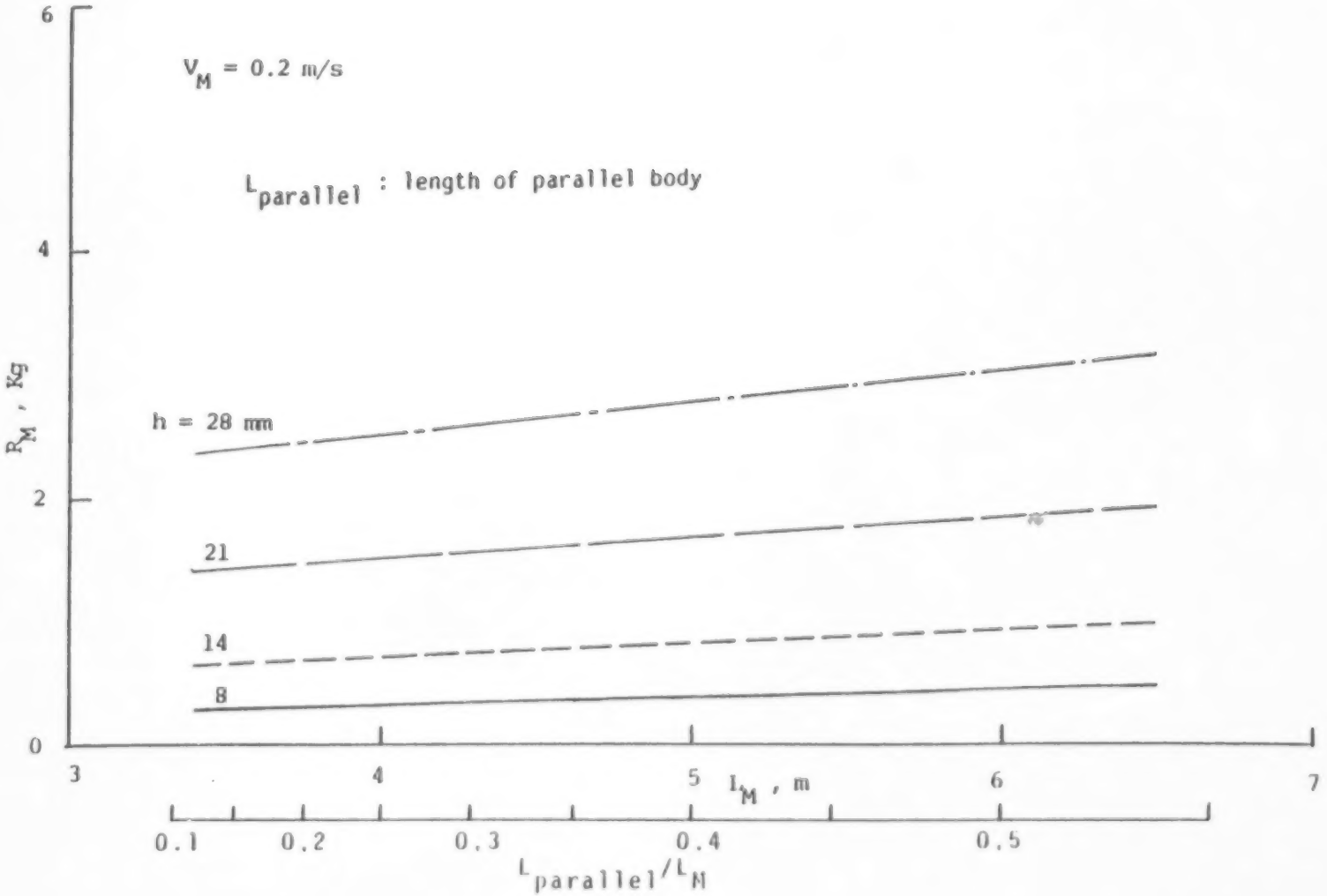


Fig. 9 EFFECT OF PARALLEL BODY LENGTH ON RESISTANCE
(Reproduced from Reference 9)

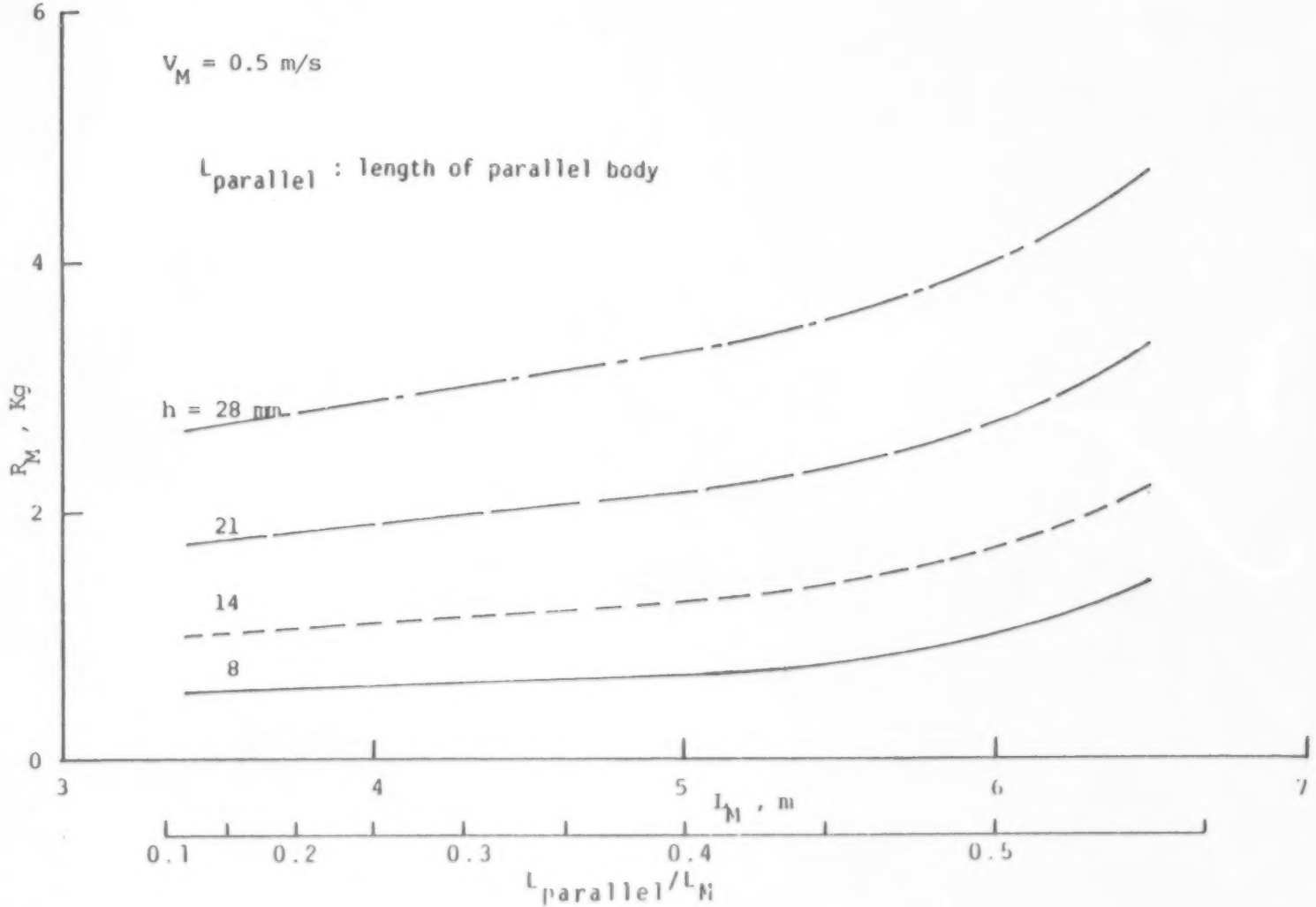
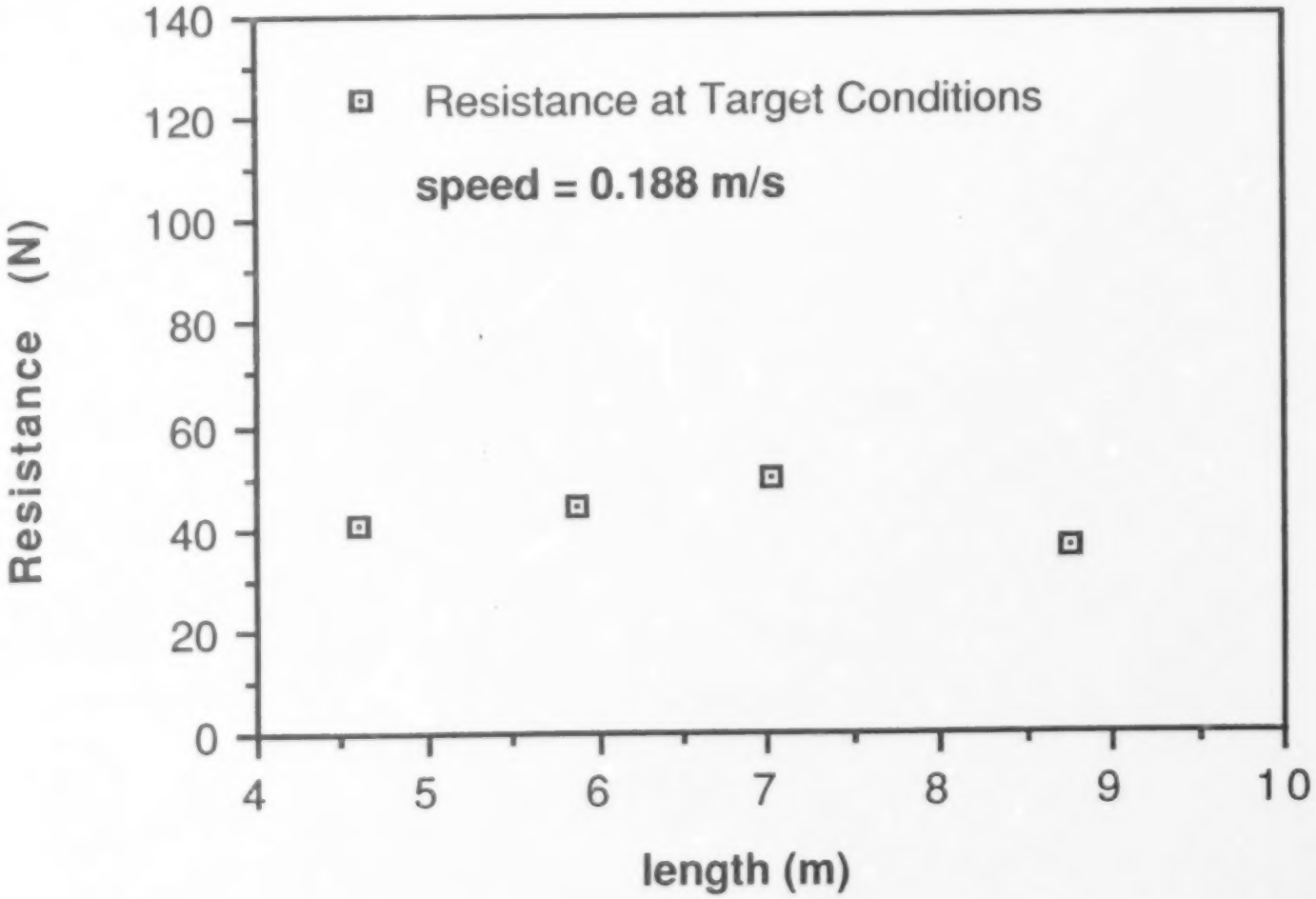
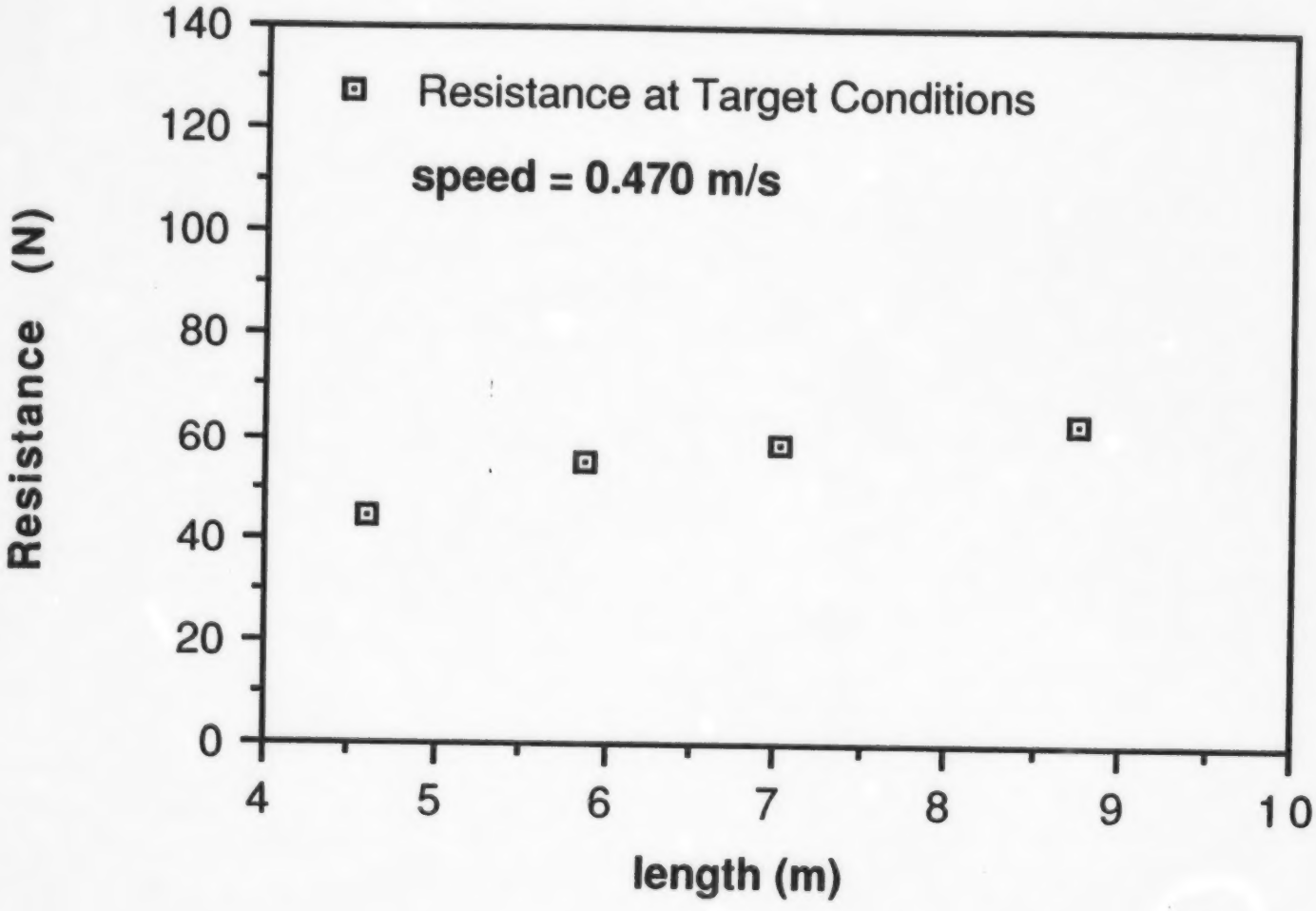


Fig. 10 EFFECT OF PARALLEL BODY LENGTH ON RESISTANCE
(Reproduced from Reference 9)

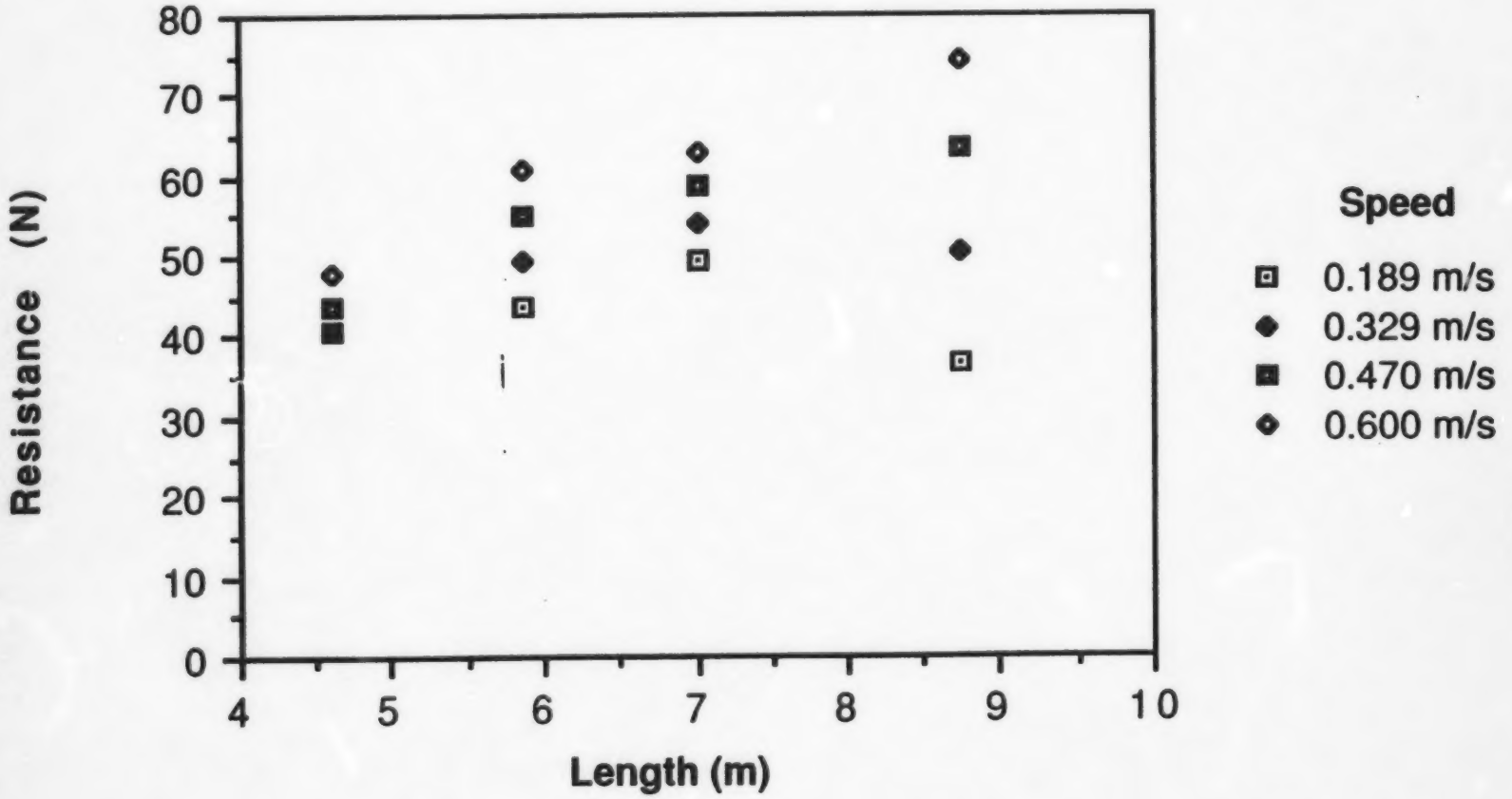
Effect of Parallel Midbody Length on Resistance



Effect of Parallel Midbody Length on Resistance



Effect of Parallel Midbody Length on Resistance



APPENDIX C

DATA CORRECTION TECHNIQUE

C. Data Correction Technique

C.1 General

The Midbody test program consisted of 14 ice sheets that ranged in target thickness from 30 to 50 mm and with a target strength of 19 kPa. Although every effort was made to ensure that the model was tested in these ice conditions, problems experienced during the refrigeration and tempering process resulted in ice conditions that departed from these standard conditions.

There are two objectives to the data correction and adjustment described in the following Appendix;

1. Recognising that some of the target strengths were not achieved within the bounds of conventional test correction procedures, adjust the data using established trends and variable interdependencies.

2. Present the data in a format that will permit additional analysis to investigate the influence of different hull parameters and variables.

This appendix describes the analysis that was conducted on those data points that were influenced by, or, due to their proximity, could have been influenced by the ice properties that were outside normal range of standard correction procedures. For the purposes of this report the lower level of strength considered to be reliable is 16 kPa.

There were a number of ice sheets in which strength measurements indicated low ice strength values in specific areas. In addition to these measured areas, it is anticipated that although the remaining ice sheet appeared to have otherwise nominally correct ice strength, the strength profile was not sufficiently comprehensive to establish the extent of each low strength area and they may have had some influence on adjacent tests.

Recognising these problems the data set has been adjusted to reflect consistent trends of strength and thickness and then curves have been generated that form a least squared fit through the data. These curves are then used in the subsequent analysis.

The ice tests were conducted at five speeds in each ice sheet, 0.02, 0.188, 0.33, 0.47 and 0.6 m/sec. The very low speed test was conducted at the end of each run to investigate any tendency of the resistance data to increase at low speeds. Since this low speed run is suspected of not following the overall trends of the remaining data it has not been discussed in the following analysis although it has been shown on each figure for completeness. It has not been incorporated into any of the curves i.e. it has not been included when developing relationships.

The following analysis is divided into sections that represent each of the ice sheets, or ice sheet sets, that were modified.

C.2 Ice Sheets #1, 2, and 3

Figure C1 presents the results from tests 1,2 and 3, corrected using a standard procedure for strength and thickness described in section 2 of the main report. It can be seen from this figure that the resistance does not conform to the generally accepted trends of increasing resistance with increasing speed and thickness. Figure C2 presents the same data in the form of Resistance vs Thickness. Comparing these figures it can be seen that the second, 40 mm, ice sheet tends to yield higher resistance results than would be expected and this is considered to be due to the low ice strength that occurred during this test. Figure C3 presents the results of the presawn ice tests which were conducted in the same ice sheet. The incorrect ice strength does not appear to have had a significant affect on the presawn data which appears to be more consistent.

Before any corrections were made to the 40 mm ice sheet on the basis of the results of the 50 and 30 mm sheets a number of other ice tests, conducted over a series of ice thicknesses were reviewed.

1. Louis S. St Laurent Model tests:

   Model scale 1:15
   Model ice target strength 30 kPa
   Model ice target thicknesses 100, 67, 47 mm

   Figure C4 presents the results from the Louis test series in the form of Resistance vs Thickness. It can be seen from the figure that the rate of change of resistance with thickness is constant. This figure cannot be directly compared with the midbody tests due to the different scale factors, however a comparison can be made by comparing the tests at full scale values. Figure C5 presents the comparison between the midbody test results and the highest and lowest speed test of the Louis program. Clearly the results indicate that the overall relationship between thickness and strength is linear and justifies some correction to the 40 mm midbody test results.

2. R-Class model test series:

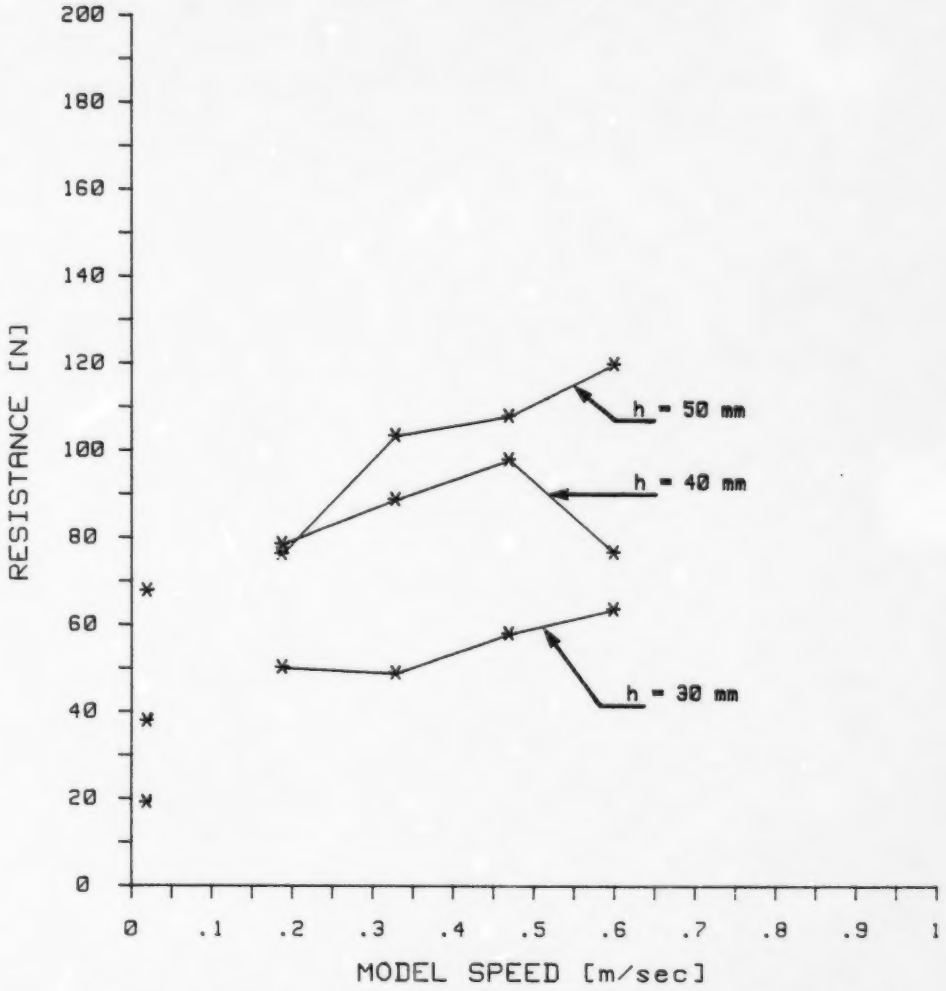
   Model scale 1:30
   Model ice target strength 30 kPa
   Model ice target thicknesses 100, 67, 47 mm

   Figure C6 presents the full scale Thickness vs Resistance for the R-Class ice breaker and the Midbody programs. The R-Class icebreaker was tested in thinner ice than the Melville Bow in the midbody program and as a result only limited comparisons can be made between these two sets of data. However it can be seen that the R-Class data does exhibit a general increase in resistance with increased ice thickness.

Based on these observations it was elected to modify the tests using the following procedure;

FIGURE C1

RESISTANCE vs SPEED FOR A RANGE OF ICE THICKNESSES (MELVILLE BOW)



Midbody test program ; Ice sheet #1 #2 and #3
. ; Existing ship length
Data corrected for ice thickness and strength
Target ice thickness = 50 40 and 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06

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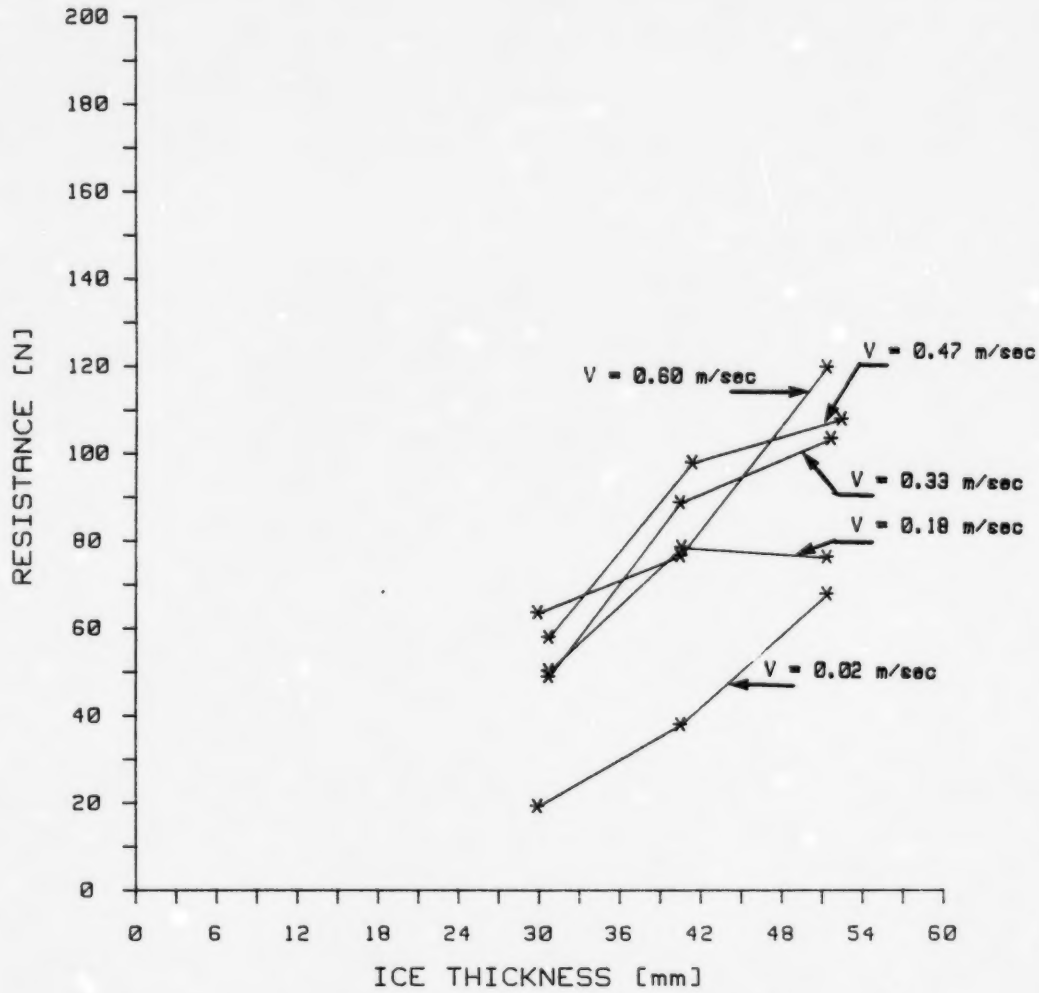
FIGURE C2

RESISTANCE vs THICKNESS OVER A RANGE OF SPEEDS (MELVILLE BOW)



Midbody test program ; Ice sheet #1 #2 and #3
. ; Existing ship length
Data corrected for strength
Target ice thickness = 50 40 and 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06

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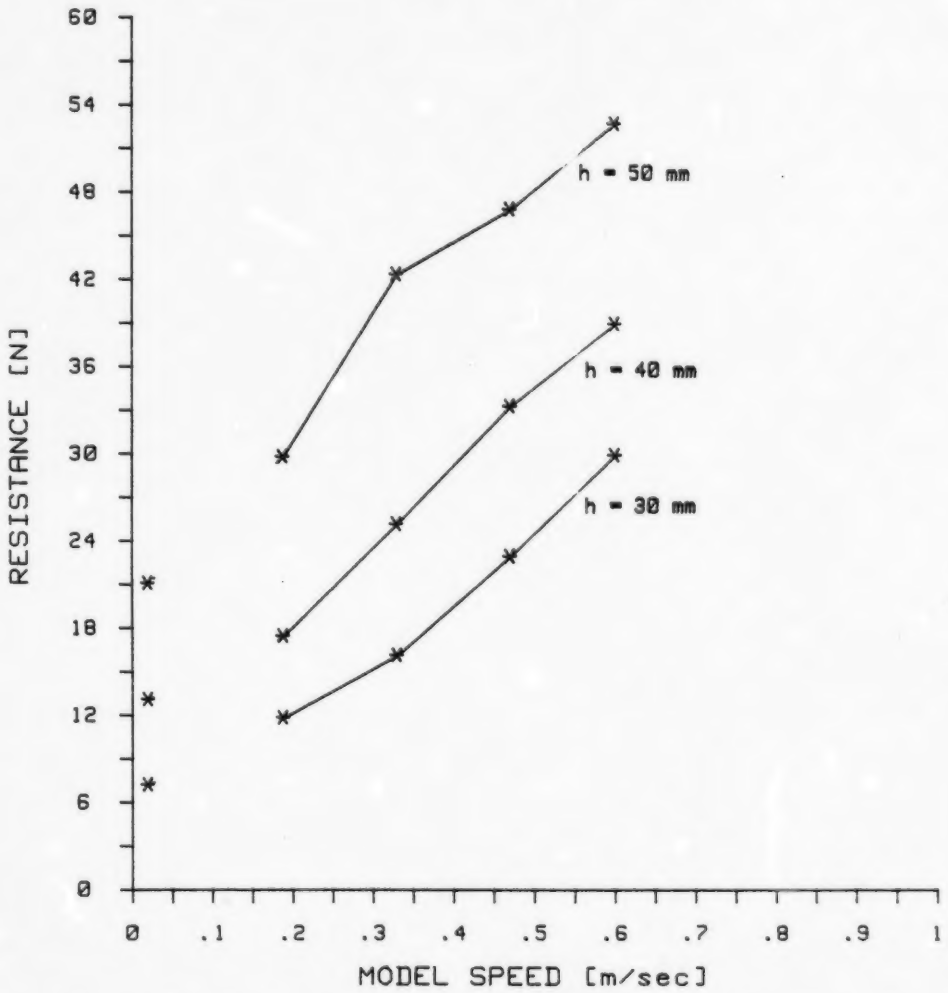
FIGURE C3

PRE SAWN RESISTANCE vs THICKNESS OVER A RANGE OF SPEED (MELVILLE BOW)



Midbody test program ; Ice sheet #1 #2 and #3
. ; Existing ship length
Data corrected for thickness
Target ice thickness = 50 40 and 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06

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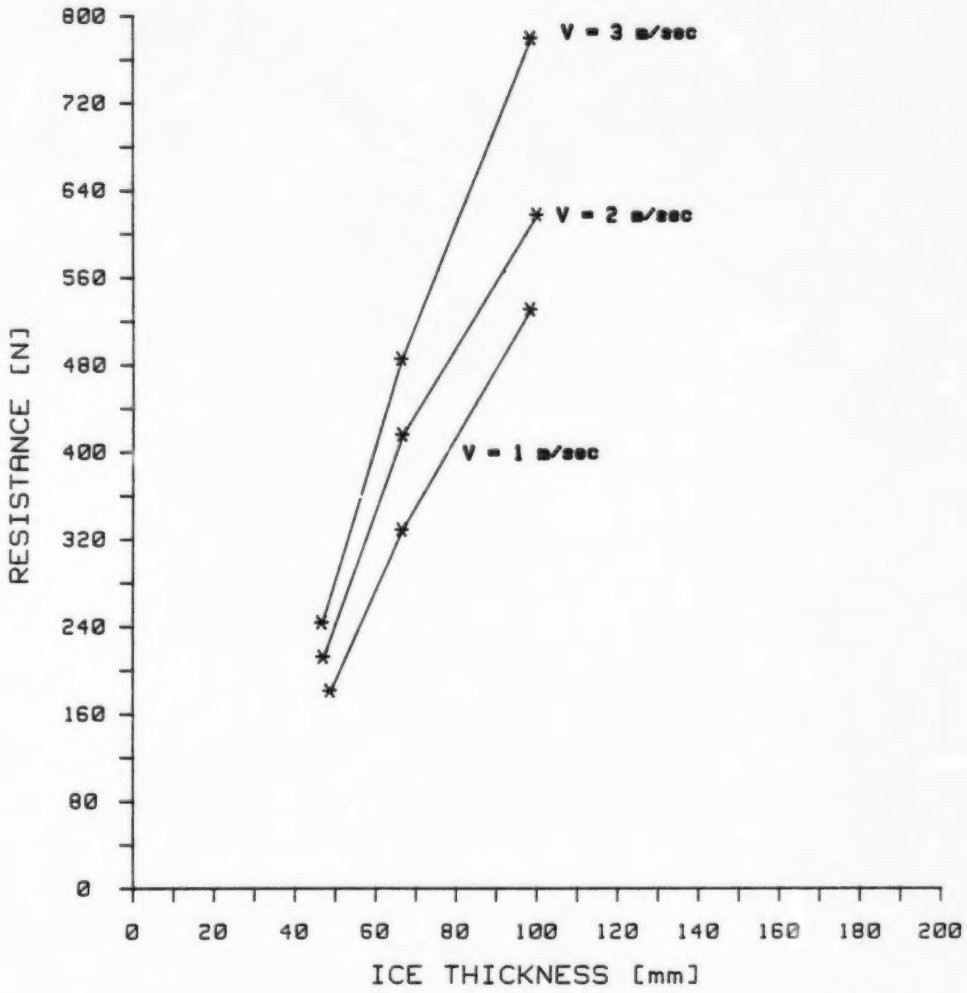
FIGURE C4

MODEL RESISTANCE vs THICKNESS OVER A RANGE OF SPEEDS



Louis test program ; Ice sheet #8 #9 and #11
; Melville bow
Data corrected for strength

Target ice strength = 19 kPa
Friction coefficient = 0.1

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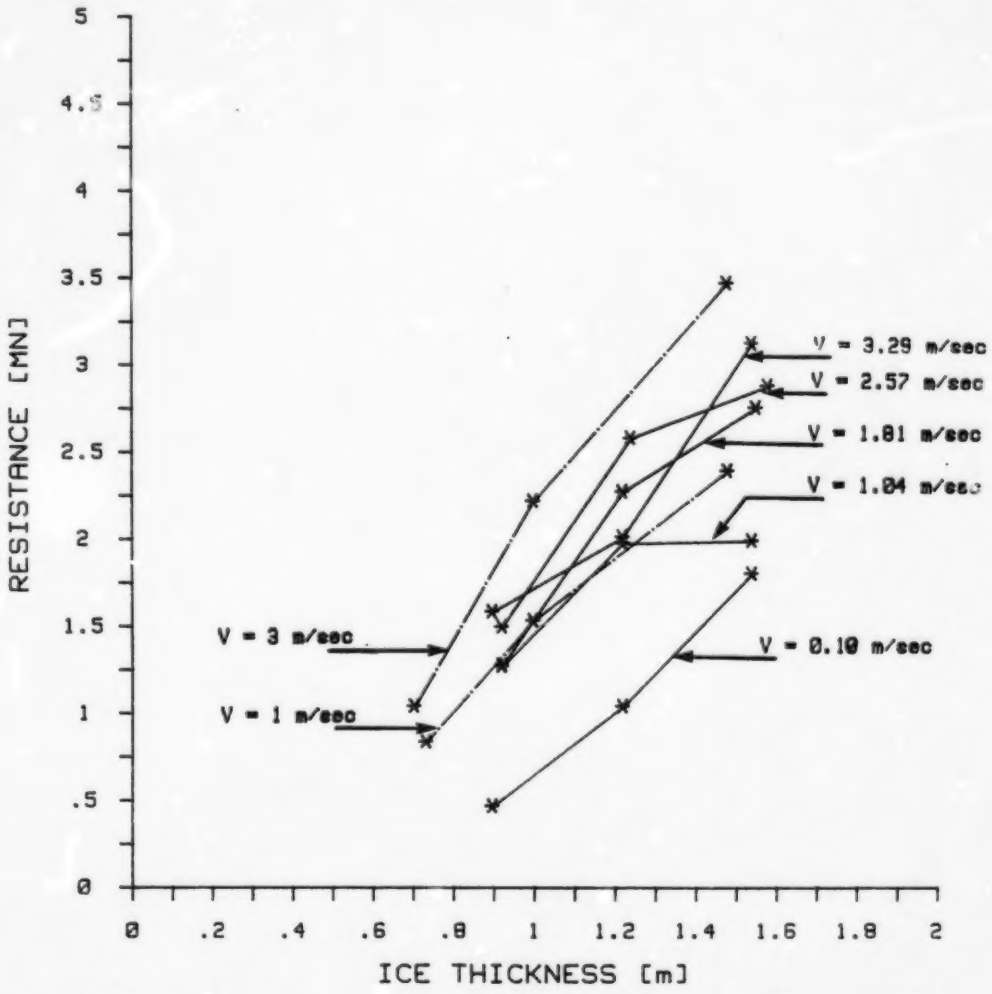
FIGURE C5

FULL SCALE RESISTANCE vs THICKNESS FOR A RANGE OF SPEED (MELVILLE BOW)



Midbody test program ; Ice sheet #1 #2 and #3
Friction test program ; Ice sheet #8 #9 and #11
Data corrected for strength
Target ice thickness = 0.9 to 1.5 m
Friction coefficient = 0.06 and 0.1
Broken line = Louis test program
Solid line = Midbody test program

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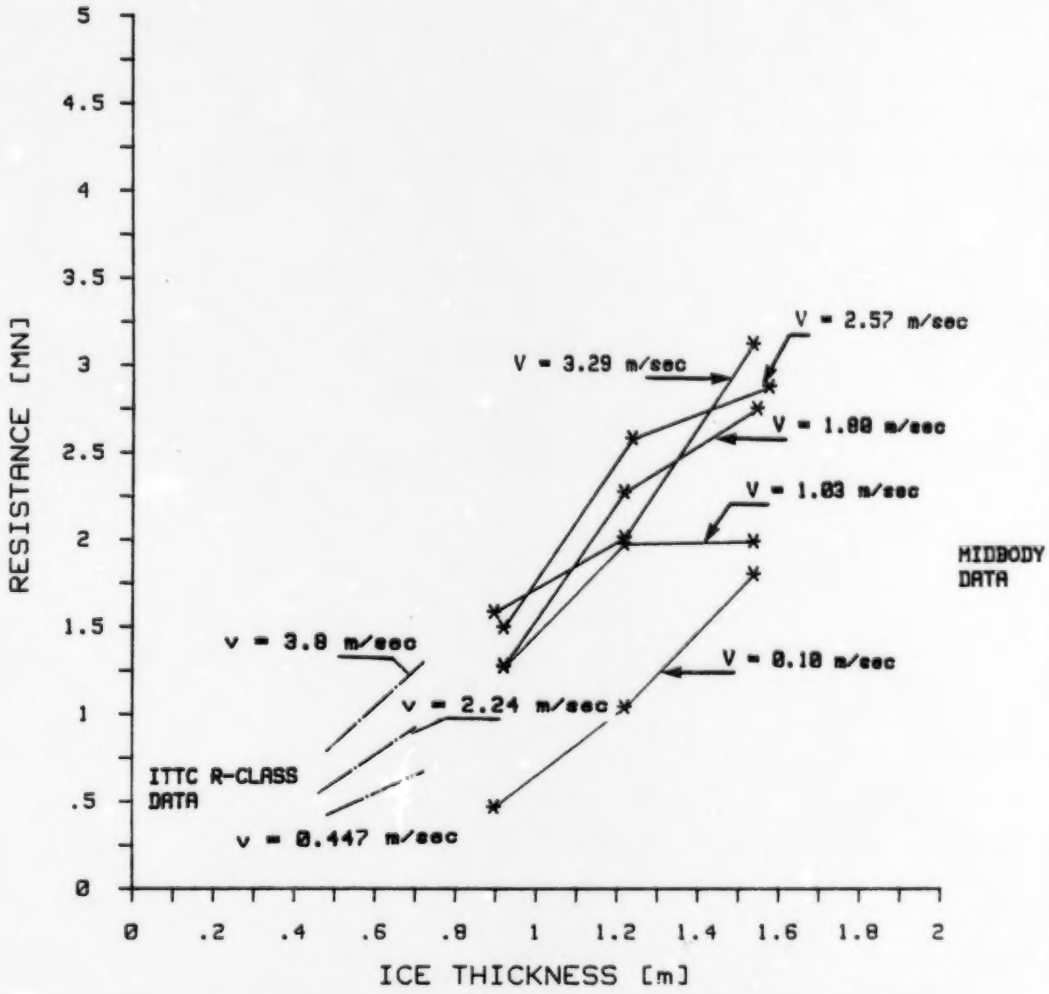
FIGURE C6

RESISTANCE vs THICKNESS FOR THE 1:20 R-CLASS AND MIDBODY PROGRAMS AT RANGE OF SPEEDS



Midbody test program ; Ice sheet #1 #2 and #3
ITTC R-Class program ; IMD test data
Data corrected for strength
Target ice thickness = 0.5 to 1.5 m
Target ice strength = 500 kPa
Friction coefficient = 0.06 and 0.1

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a) The data from the 40 mm ice sheet at 0.6 m/sec was recalculated based on an interpolation between the 30 and 50 mm ice sheets at the same speed.

b) The data from the 40 mm ice sheet at 0.47 m/sec was recalculated based on an interpolation between the 30 and 50 mm ice sheets at the same speed.

c) The data from the 50 mm ice sheet at 0.329 m/sec was adjusted using linear interpolation to be consistent with the 0.6, 0.47 and 0.188 m/sec data points (see Figure C1). The data from the 40 mm ice sheet at 0.329 m/sec was then recalculated based on an interpolation between the 30 and the corrected 50 mm ice sheet at the same speed.

d) The 30 mm ice sheet at 0.188 m/sec was adjusted using linear interpolation to be consistent with the 0.6, 0.47 and 0.329 m/sec data points. The 40 mm ice sheet at 0.188 m/sec was recalculated based on an interpolation between the corrected 30 and the 50 mm ice sheets at the same speed.

The results of these corrections are shown on Figure C7 which presents the Resistance vs Thickness relationship for the model of the ARCTIC with the ship's existing configuration. Figure C7 presents a comparison between the corrected and uncorrected data. A further comparison may be made between the rate of change of resistance with strength before and after these corrections. This rate of change is simply the slope of the resistance line when plotted against strength. Figure C8 presents this rate of change before and after the corrections. It can be seen from the figure that the adjusted data conforms more consistently and further justifies the use of these particular corrections.

Clearly, these corrections have, to all intense and purposes regenerated the 40 mm ice sheet from the 30 and 50 mm tests. The reason for the low quality of data from the 40 mm ice sheet is thought to be the result of the very low ice strength and was manifested with the extremely 'plastic' nature of the ice observed during the test. Significantly more ice deflection and bending and less cracking and fracture was observed than with either the first or third ice sheets.

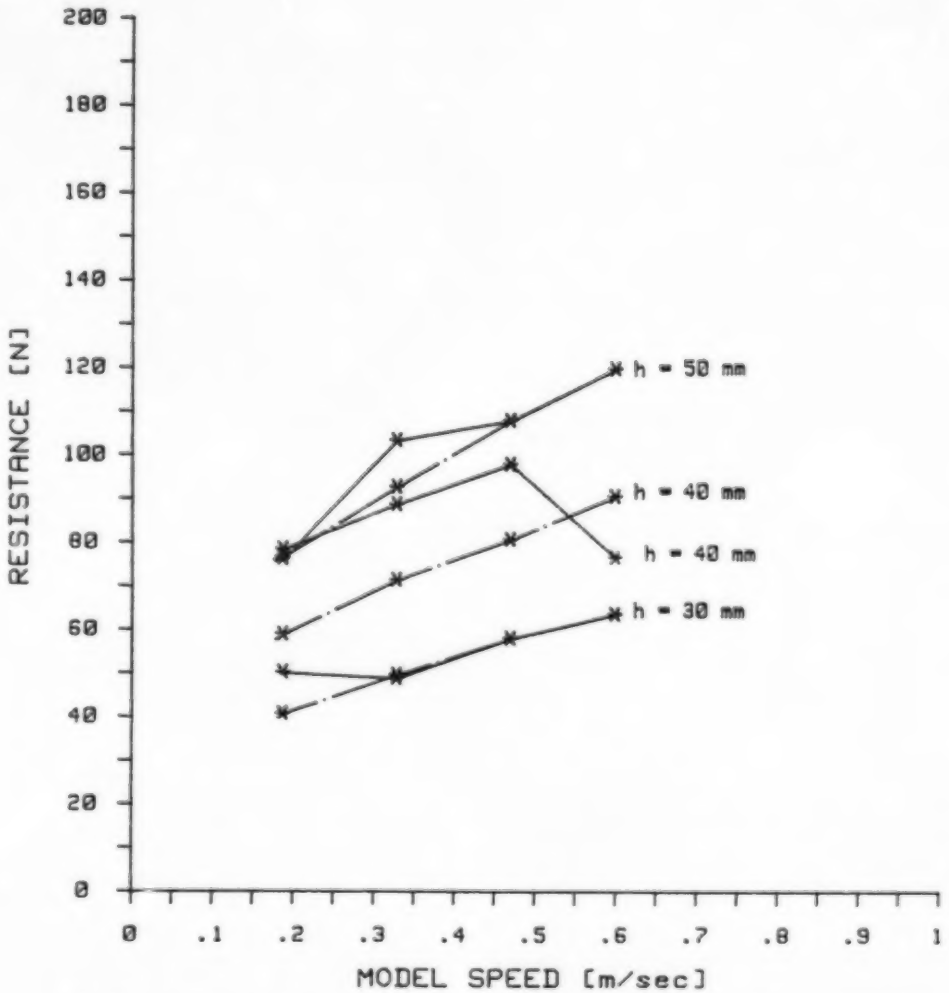
However, it should also be noted that apart from the low ice strength, the other parameters associated with the ice sheet (Appendix C) are not unusual. This is of particular concern in a general case considering the clearly observable difference in the ice breaking mechanism discussed above.

C.3 Ice Sheets #7

The 0.188 m/sec data point in ice sheet number 7 was associated with a flexural strength of 13 kPa. Figure C9 presents the data as Resistance vs Speed and highlights the inconsistent 0.188 m/sec data point. Figure C10 presents the same test results as a function of rate of change of resistance with strength against speed. The 0.188 m/sec data point clearly shows a higher strength dependency than the remaining tests. This data

FIGURE C7

COMPARISON OF RESISTANCE vs SPEED
BEFORE AND AFTER CORRECTION
(MELVILLE BOW)



Midbody test program ; Ice sheet #1 #2 and #3
Target ice thickness = 30 40 and 50 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06
Broken line = Corrected data
Solid line = Uncorrected data

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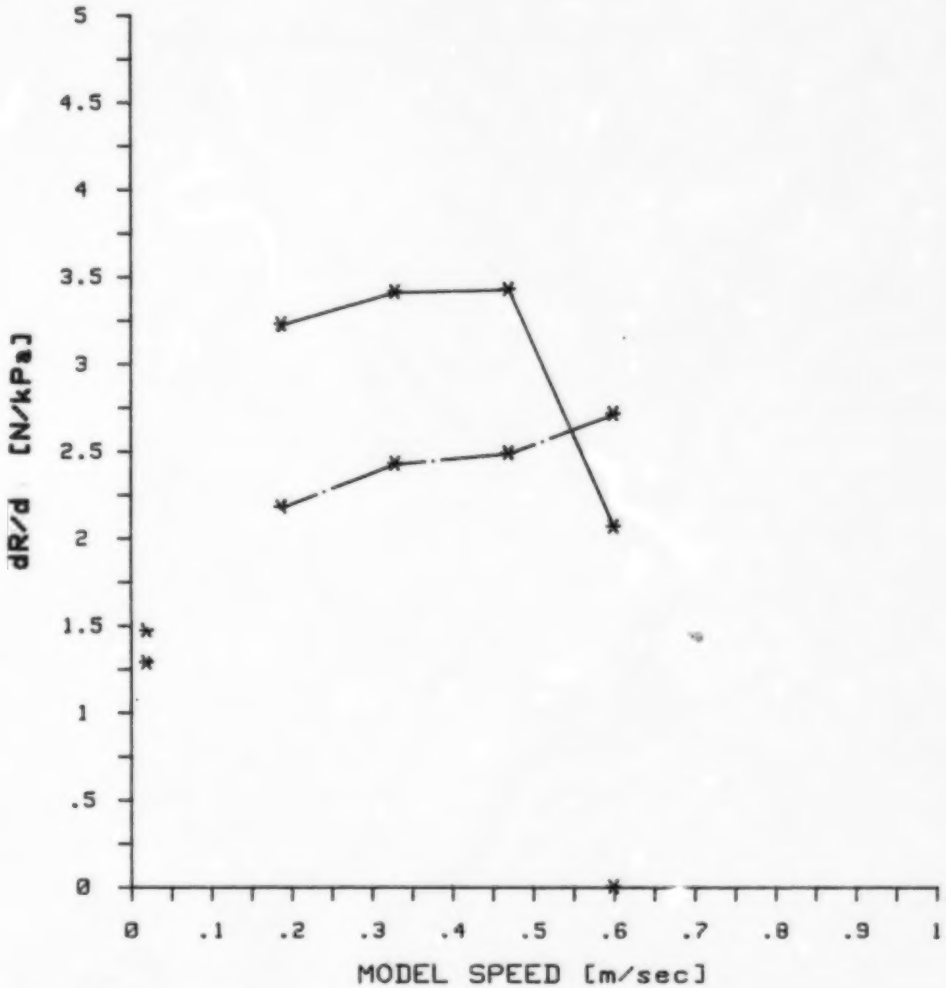
FIGURE C8

COMPARISON BETWEEN RATE OF CHANGE OF RESISTANCE
BEFORE AND AFTER CORRECTION

(MELVILLE BOW)



Midbody test program ; Ice sheet #2
Data corrected for thickness
Target ice thickness = 40 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06
Broken line = Corrected data
solid line = Uncorrected data

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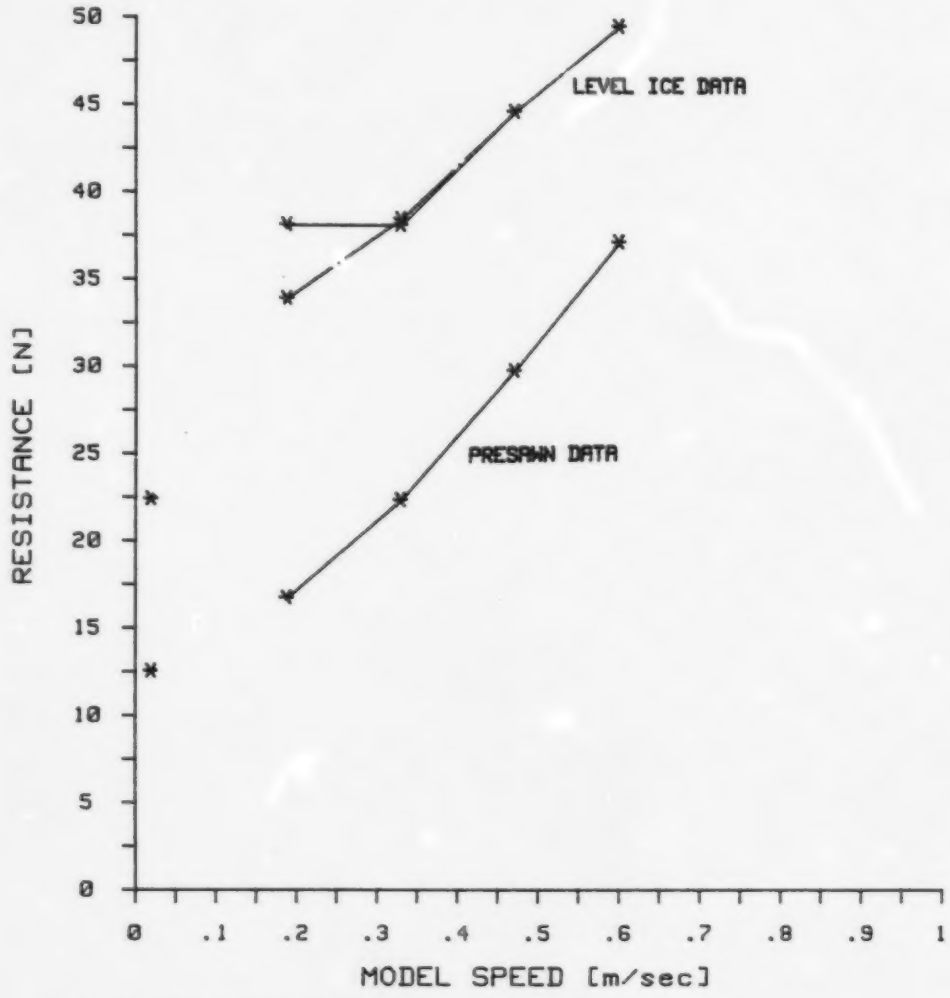
FIGURE C9

COMPARISON BETWEEN RESISTANCE vs SPEED BEFORE AND AFTER CORRECTION

(MELVILLE BOW)



Midbody test program ; Ice sheet #7
Data corrected for thickness and strength
Target ice thickness = 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06
Broken line = Corrected data
Solid line = Uncorrected data

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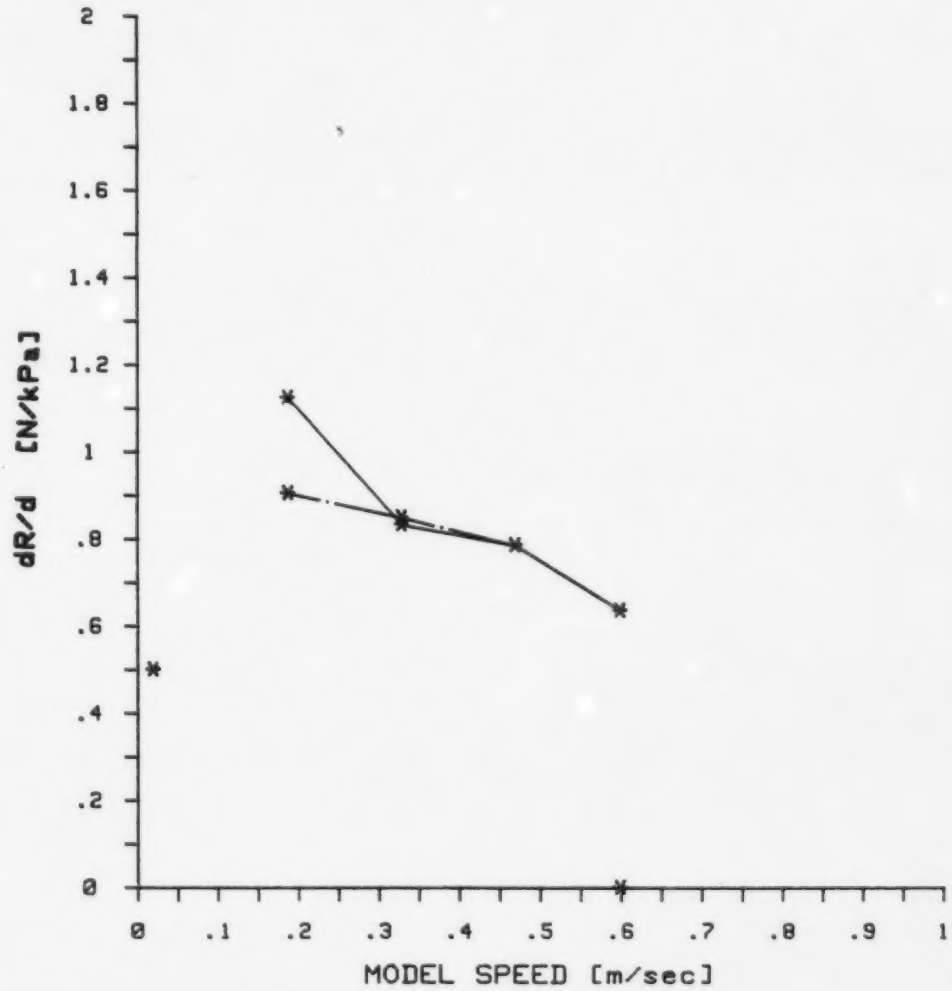
FIGURE C10

COMPARISON BETWEEN RATE OF CHANGE OF RESISTANCE WITH STRENGTH BEFORE AND AFTER CORRECTION

(MELVILLE BOW)



Midbody test program ; Ice sheet #7
Data corrected for thickness
Target ice thickness = 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06
Broken line = Corrected data
Solid line = Uncorrected data

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point was adjusted by taking the average between the values obtained by extrapolating the 0.6, 0.47 and 0.33 m/sec data from the Resistance vs Speed curve and the rate of change of resistance with Strength vs Speed curve. The resultant data is presented as the broken lines on Figures C9 and C10.

C.4 Ice Sheets #8

The strength of the ice associated with the 0.47 m/sec data point was very marginally under the lower limit of strength acceptability. However, reviewing Figure C11, it is clear that the rate of change of resistance with strength is either too low at 0.6 m/sec or too high at .47 m/sec depending on whether the curve should be tending to rise or fall respectively. Alternatively the presawn 0.6 m/sec data point may be too high and this is affecting the rate of change of resistance with strength.

From the available midbody program data it is not clear how this data set should be adjusted, particularly since the friction coefficient for this test was 0.004. However, similar tests were conducted as part of the friction test program.

Figure C12 shows the comparison between three friction tests, each with a bow friction coefficient of 0.004, together with the data from the midbody test #8. The friction tests were conducted in thicker ice (50 mm) and were not shortened versions of the ship, however there does appear to be a trend for the rate of change of resistance with strength to increase with increasing speed. If this is the case then the 0.6 m/sec rate of change of resistance with strength is too low and should be adjusted upwards. This can be accomplished by increasing the level ice resistance data point or decreasing the presawn ice data point. Figure C13 presents the comparison between the presawn midbody tests #8 and #9, the short ship with the Melville and Original Bow, and the 0.004 friction coefficient tests from the friction program. The presawn data is consistent and no evidence of unusually high values exists.

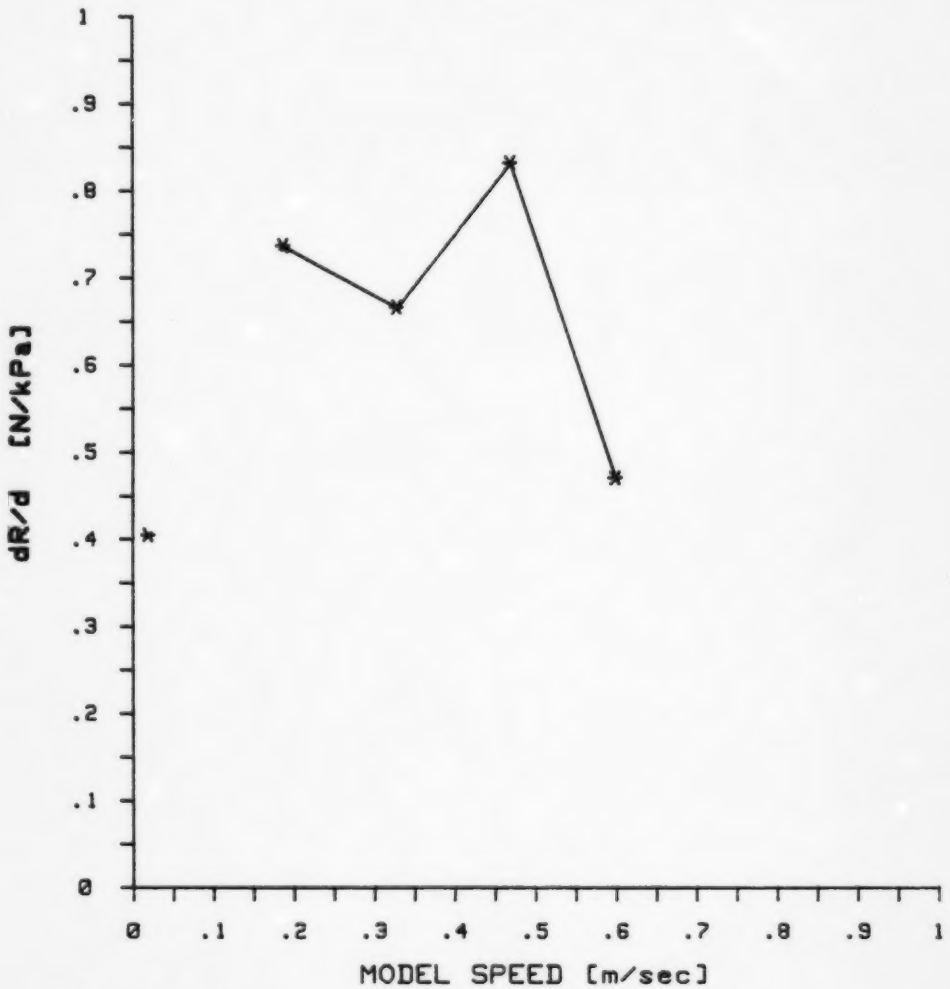
The alternative to decreasing the presawn value is to increase the level ice resistance data point. This has been done by extrapolating the Resistance vs Speed curve from the 0.33 and 0.47 m/sec data points. Figures C14 and C15 present the corrected data in the form of Resistance vs Speed and Rate of change of resistance with Strength vs Speed. It can be seen from these curves that the corrected data conforms more consistently with overall data trends.

C.5 Ice Sheets #9

Two data points in ice sheet 9 were below the lower limit of strength acceptability. However, following a review of the data there is no apparent inconsistency and the data conforms to the established trends of ice thickness, strength and speed. As a result no adjustments were made to this data set.

FIGURE C11

RATE OF CHANGE OF RESISTANCE
WITH STRENGTH vs SPEED
(MELVILLE BOW)



Midbody test program ; Ice sheet #8
Data corrected for thickness
Target ice thickness = 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.004

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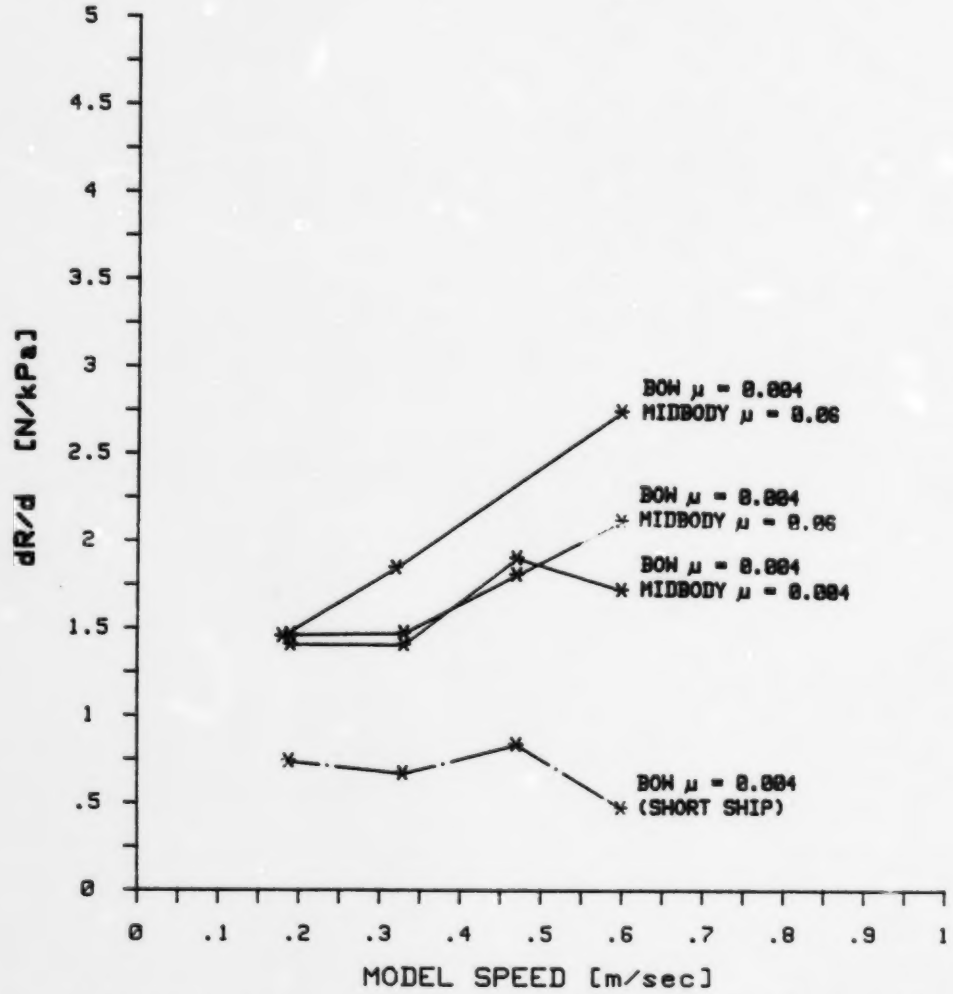
FIGURE C12

COMPARISON BETWEEN RATE OF CHANGE OF RESISTANCE WITH STRENGTH FOR MIDBODY AND FRICTION PROGRAMS

(MELVILLE BOW)



Friction test program ; Ice sheet #3 #5 and #9
Midbody test program ; Ice sheet #8
Data corrected for thickness
Target ice thickness = 30 and 50 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06 and 0.004
Broken line = Midbody program
Solid line = Friction program

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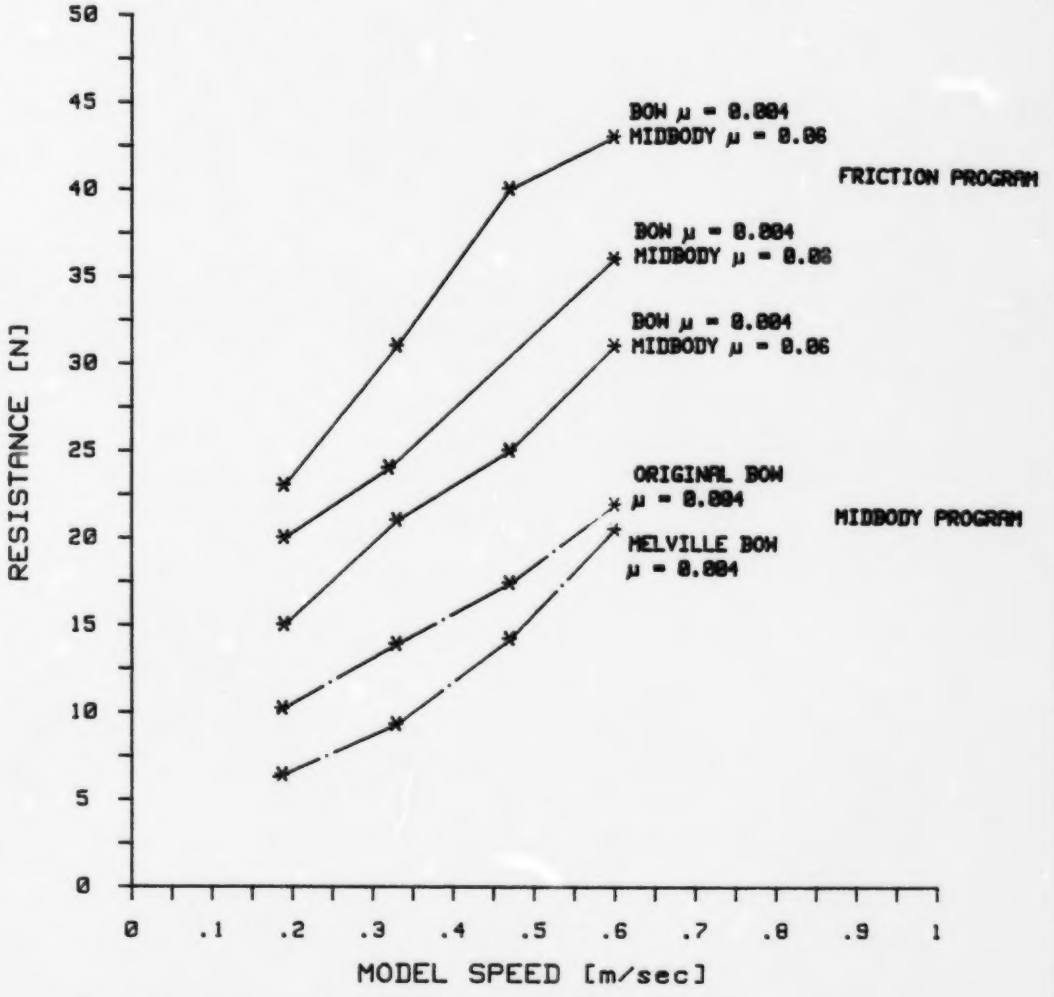
FIGURE C13

COMPARISON BETWEEN PRE-SAWN RESISTANCE vs SPEED FROM FRICTION AND MIDBODY PROGRAMS



Friction test program ; #3 #5 and #9
Midbody test program ; #8 and #9
. ; Short models
Data corrected for thickness and strength
Target ice thickness = 30 and 50 mm
Target ice strength = 19 kPa
Friction coefficient = 0.004 and 0.06

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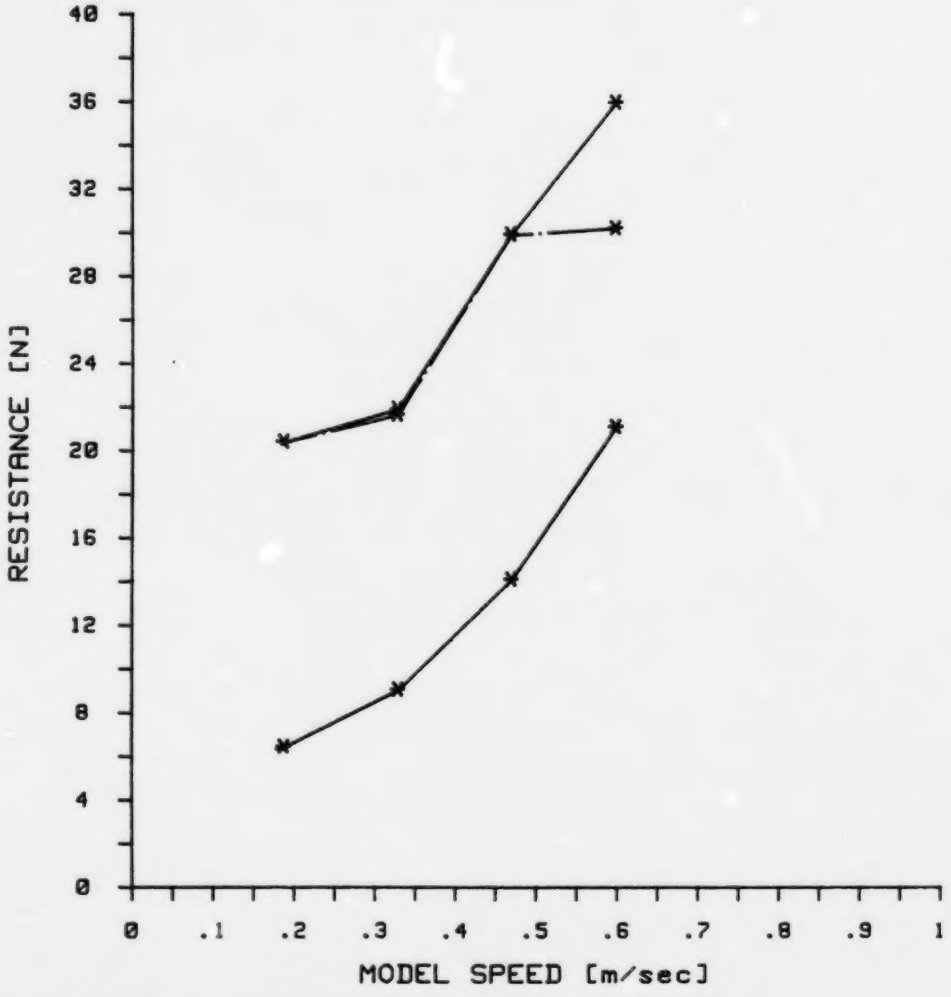
FIGURE C14

COMPARISON BETWEEN PRE-SAWN AND LEVEL ICE
RESISTANCE vs SPEED BEFORE AND AFTER CORRECTION
(MELVILLE BOW)



Midbody test program ; Ice sheet #8
Data corrected for thickness and strength
Target ice thickness = 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.004
Broken line = Uncorrected data
Solid line = Corrected data

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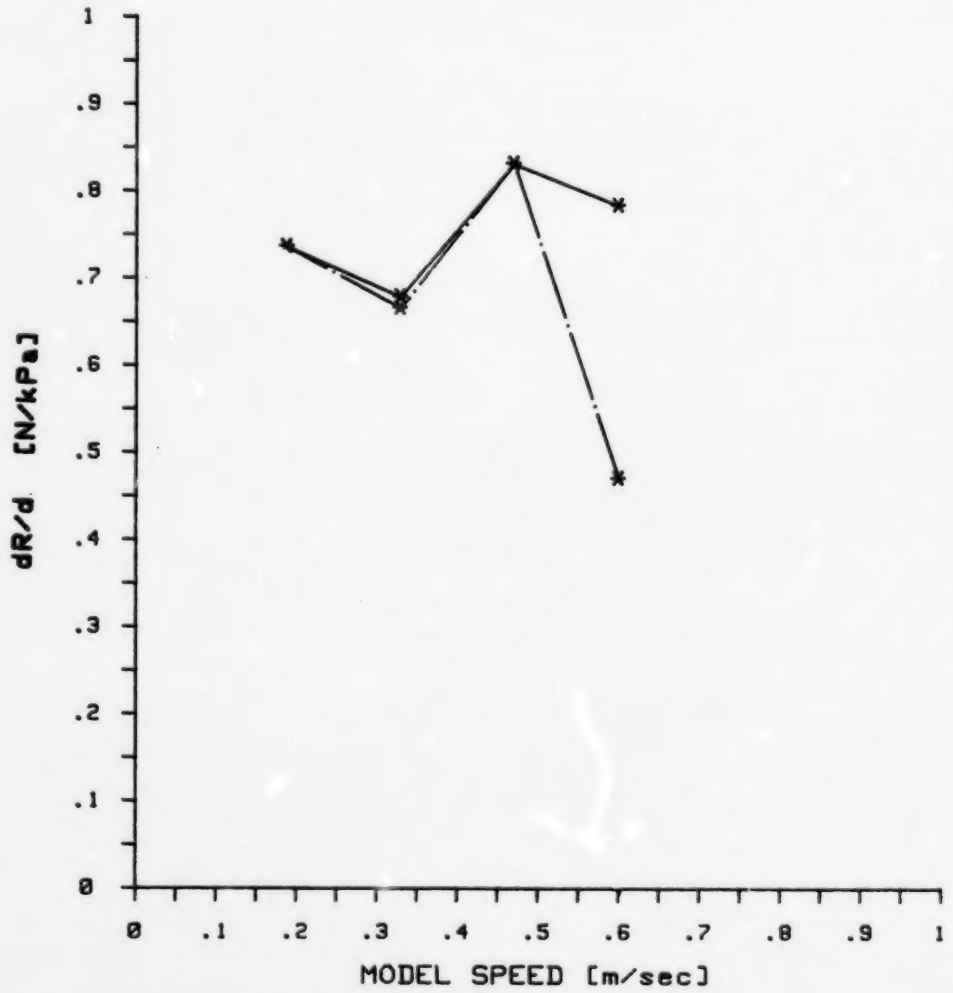
FIGURE C15

COMPARISON BETWEEN RATE OF CHANGE OF RESISTANCE WITH STRENGTH BEFORE AND AFTER CORRECTION

(MELVILLE BOW)



Midbody test program ; Ice sheet #8
Data corrected for thickness and strength
Target ice thickness = 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.004
Broken line = Uncorrected data
Solid line = Corrected data

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C.6 Ice Sheets #10

The strength of the ice associated with the 0.188 m/sec data point was below the lower limit of strength acceptability. Figure C16 presents the level ice and presawn Resistance vs Thickness for this data set. Clearly the low strength, 0.188 m/sec data point is higher than would be expect, together with the 0.47 m/sec data point which was associated with an ice flexural strength of 17.7 kPa. There is little basis for correcting this set of data since there would appear to be at least two inconsistent data points. Following a review of the data it was elected to adjust the 0.188 and 0.47 m/sec points based on the presawn ice sheets and the rate of change of resistance and strength as a function of speed from the 0.6 and 0.33 m/sec points. Figure C17 shows the basis of the correction with the solid lines representing the original data, and the broken lines the adjusted data. The corrected data is also compared with the original data in Figure C18 as a function of Resistance vs Speed.

C.7 Ice Sheets #12

Ice sheet #12 was conducted without low ice strength problems, however, the Resistance vs Speed curve, shown in Figure C19, shows the 0.6 m/sec data point with a lower resistance than the lower speed 0.47 m/sec resistance. Unfortunately there is no evidence of ice property variations that could account for this irregularity and as a result an arbitrary decision was taken to correct the data point on a basis of extrapolating the rate of change of resistance and strength from the 0.33 and 0.48 m/sec data. The adjusted data point is shown on Figure C19.

C.8 Ice Sheets #13

Based on a review of the Resistance vs Thickness and Resistance vs Strength curves it was elected to modify the 0.47 m/sec data point as shown in Figure C20. The resultant data set is more consistent with acceptable trends.

C.9 Ice Sheets #14

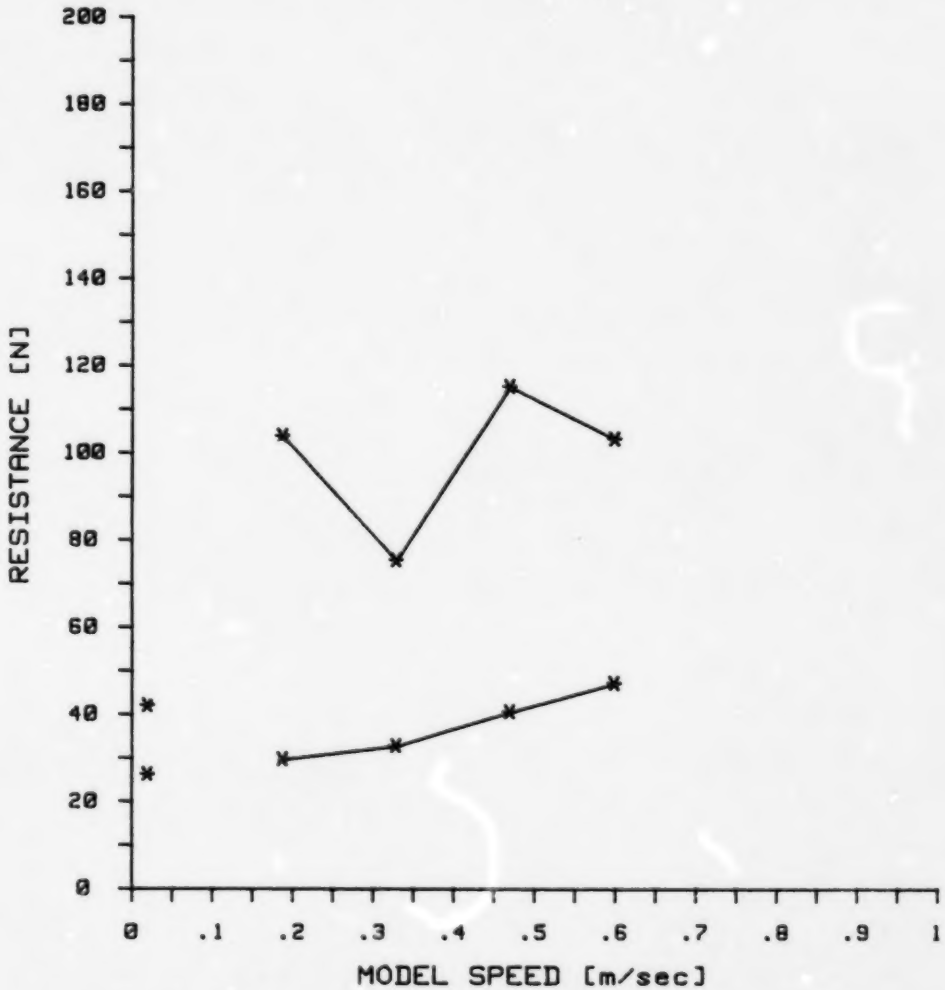
The strength of the ice associated with the 0.47 m/sec data point was below the lower limit of strength acceptability. The result of the low strength ice associated with this data point can be seen in Figure C21 and a brief inspection of the data indicates that although the 0.47 m/sec data appears high, there are other inconsistencies with the data set and three of the data points were adjusted based on a comparison with other similar ice sheets. Figures C22 and C23 and C24 present the basis for the adjustment.

Figure C22 compares the Resistance vs Speed results for ice sheet #14 with the other ice sheets associated with the Melville bow and friction coefficient of 0.06. The difference between these model tests is length only. It can be seen that the influence of length is insignificant at the low speed, with the exception of ice sheet #14 which shows a significantly

FIGURE C16

COMPARISON BETWEEN PRE-SAWN AND LEVEL
ICE RESISTANCE vs SPEED

(ORIGINAL BOW)

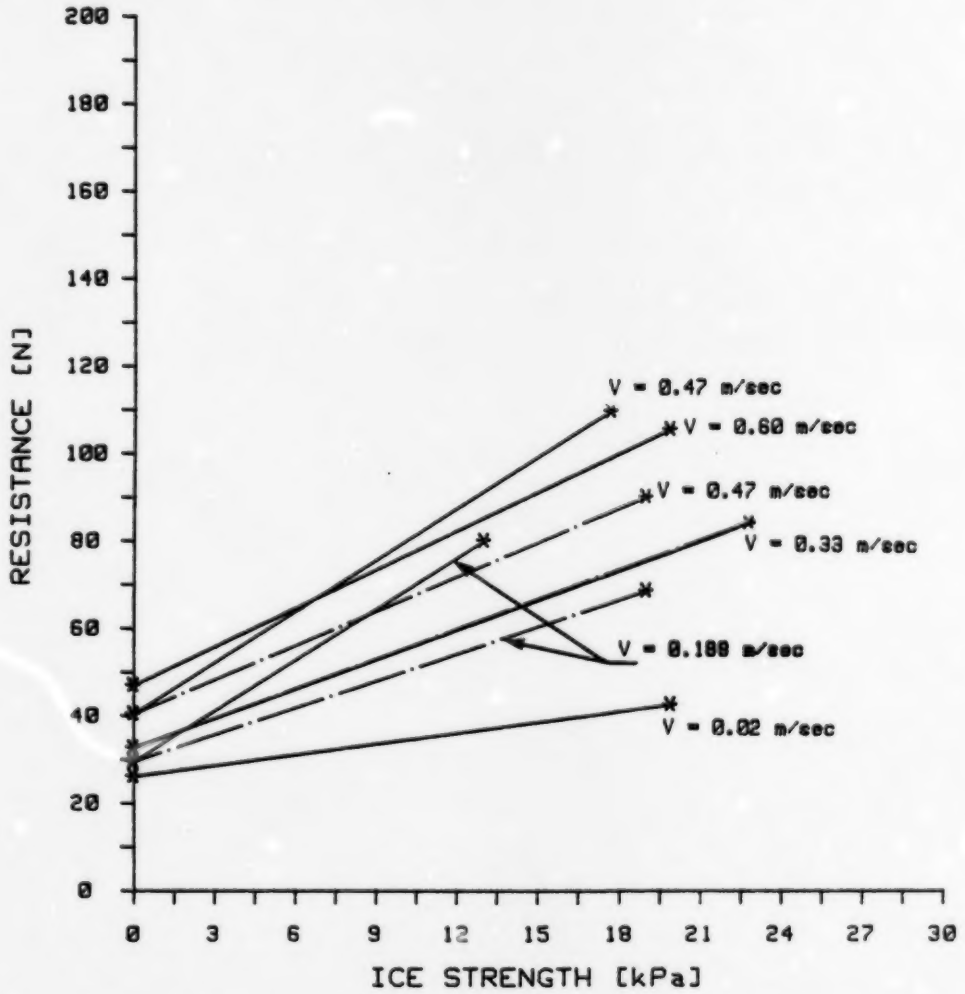


Midbody test program ; Ice sheet #10
Data corrected for ice thickness and strength
Target ice thickness = 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06

FIGURE C17

COMPARISON BETWEEN RESISTANCE vs ICE STRENGTH BEFORE AND AFTER CORRECTION

(ORIGINAL BOW)



Midbody test program ; Ice sheet #10
Data corrected for ice thickness and strength
Target ice thickness = 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06
Broken line = Corrected data
Solid line = Uncorrected data

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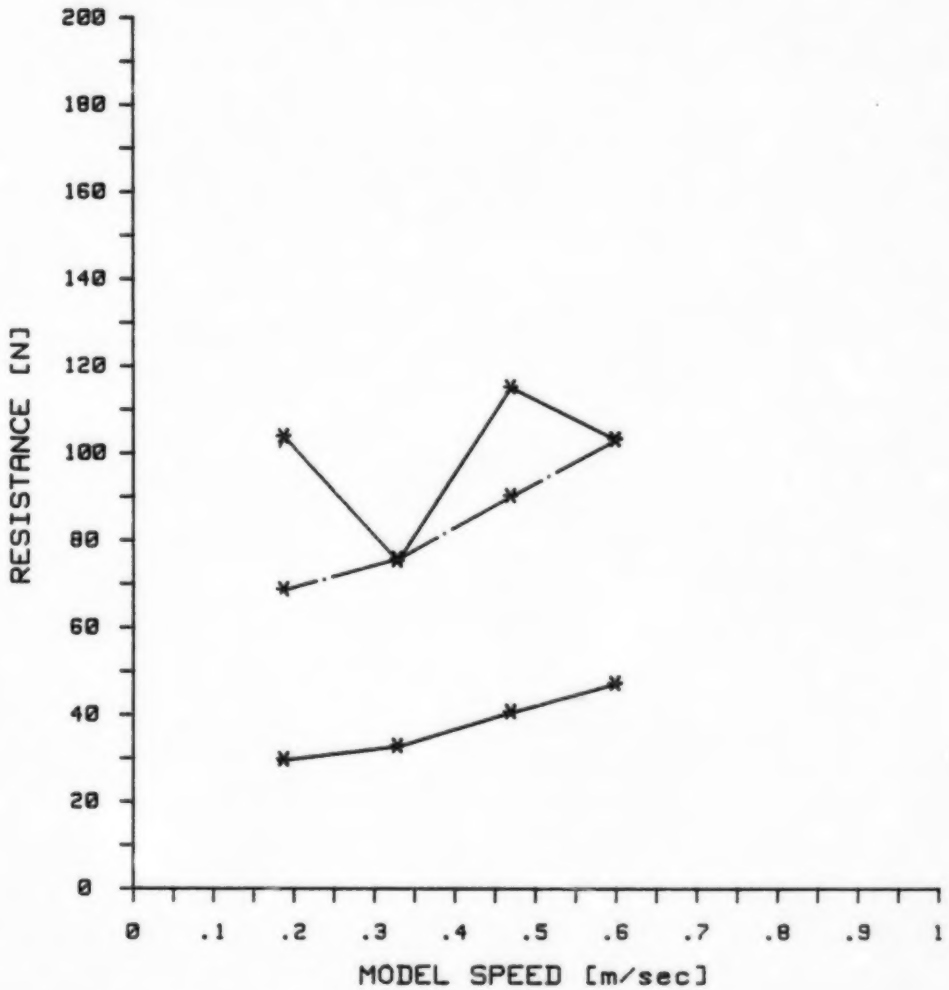
FIGURE C18

COMPARISON BETWEEN RESISTANCE vs SPEED
BEFORE AND AFTER CORRECTION

(ORIGINAL BOW)

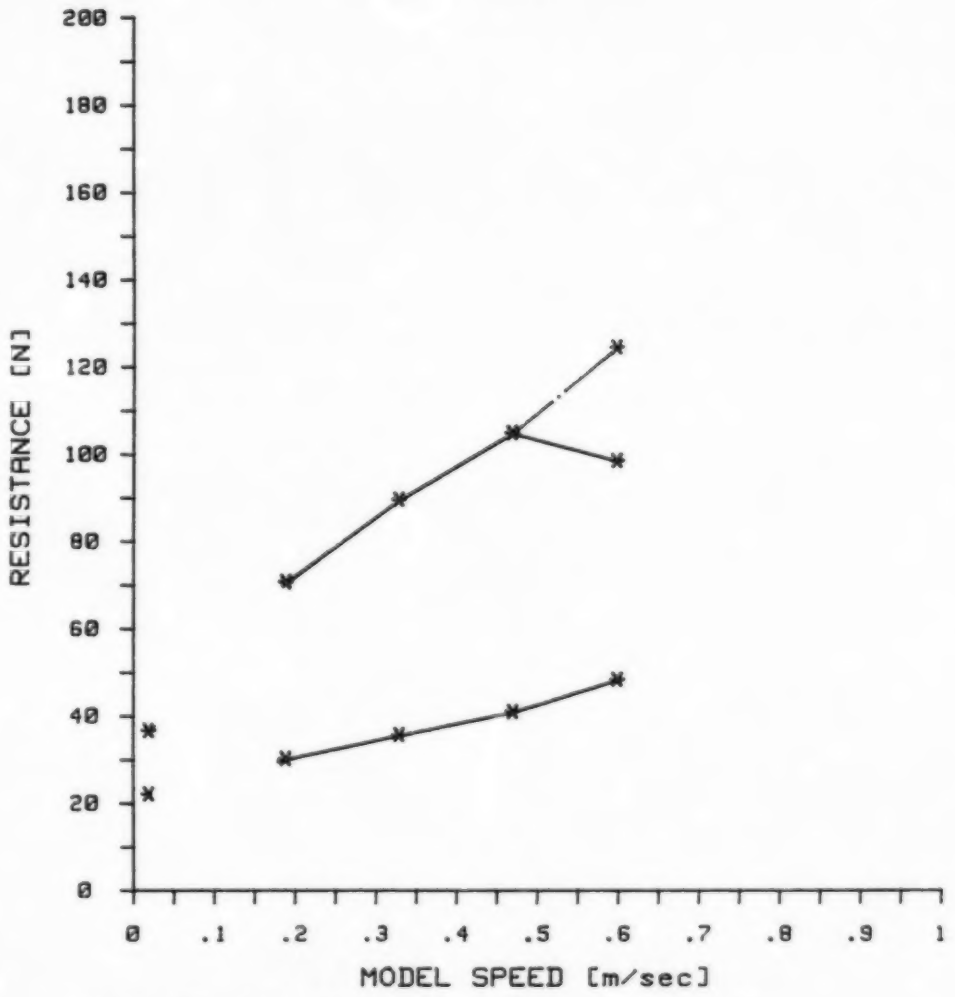


Midbody test program ; Ice sheet #10
; Original bow - short ship
Data corrected for thickness and strength
Target ice thickness = 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06
Broken line = Corrected data
Solid line = Uncorrected data

FIGURE C19

COMPARISON BETWEEN PRE-SAWN RESISTANCE
vs SPEED BEFORE AND AFTER CORRECTION

(ORIGINAL BOW)



Midbody test program ; Ice sheet # 12
. ; Original bow - long model
Data corrected for thickness and strength
Target ice thickness = 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06
Broken line = Corrected data
Solid line = Uncorrected data

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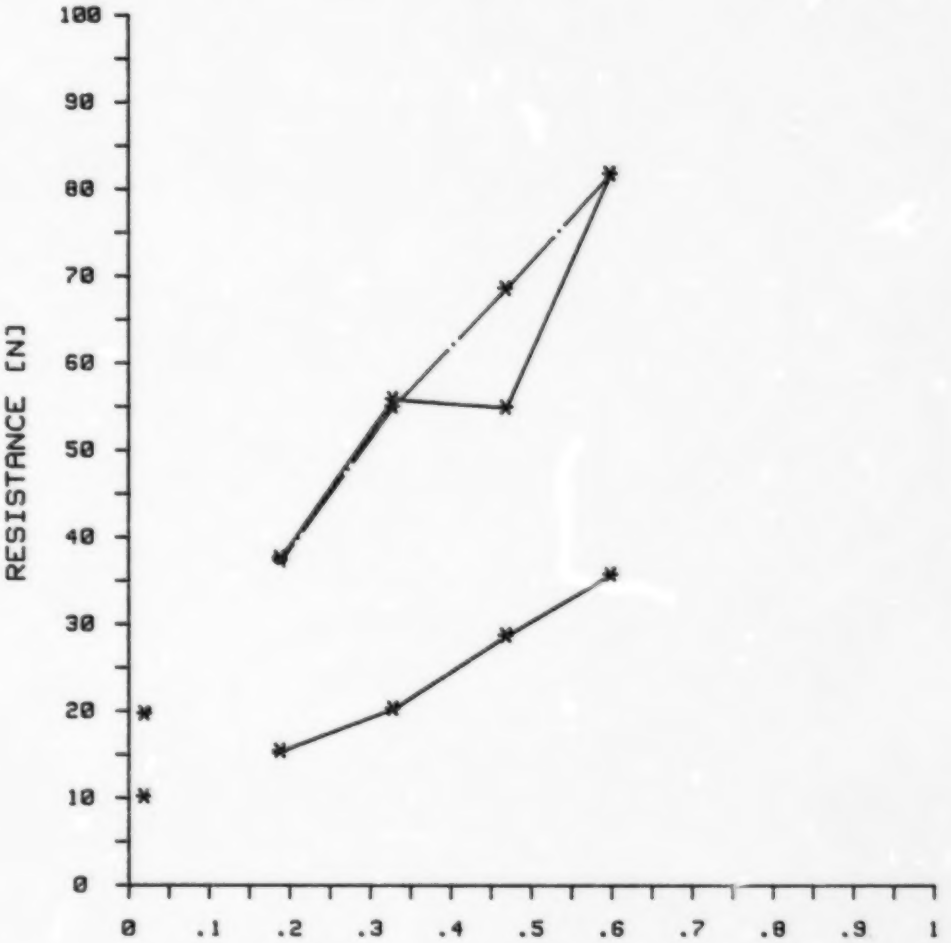
FIGURE C20

COMPARISON BETWEEN PRE-SAWN RESISTANCE vs SPEED BEFORE AND AFTER CORRECTION

(MELVILLE BOW)



Midbody test program ; Ice sheet #13
. ; Melville bow - 1.7 x Midbody
Data corrected for ice thickness and strength
Target ice thickness = 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06
Broken line = Corrected data
Solid line = Uncorrected data

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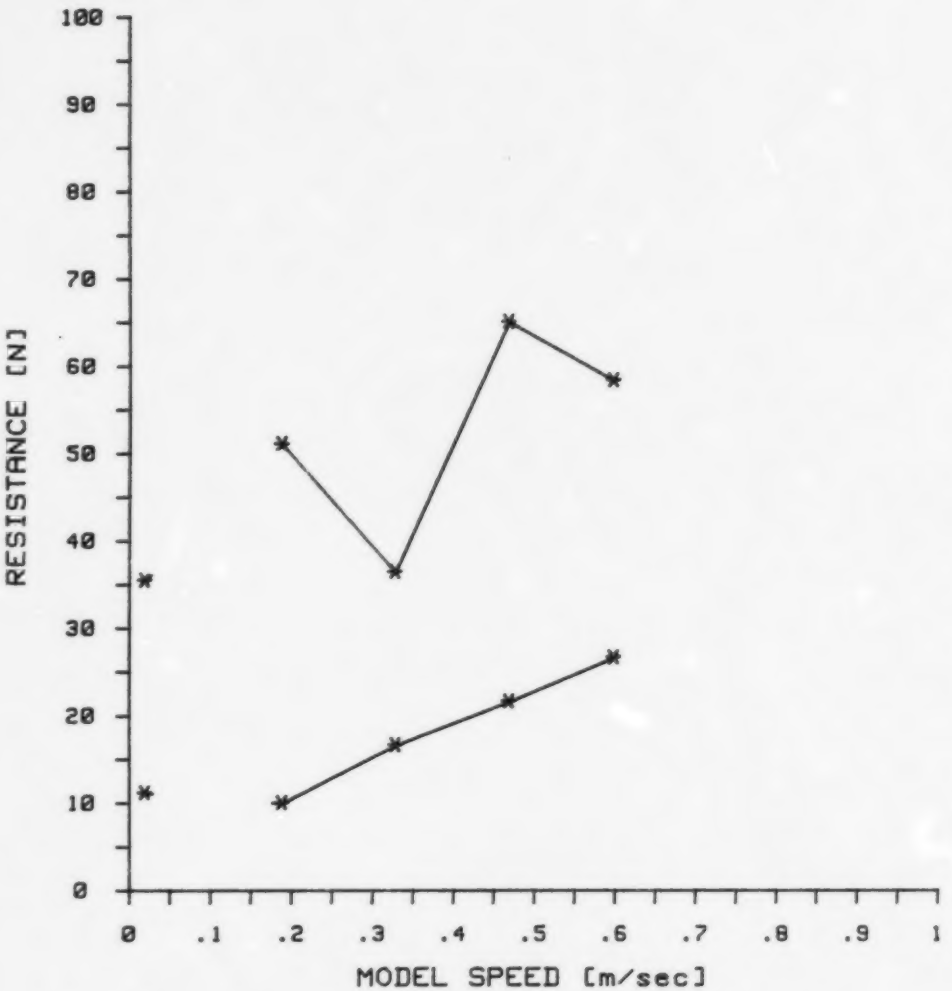
FIGURE C21

PRE-SAWN AND LEVEL ICE RESISTANCE vs SPEED

(MELVILLE BOW)



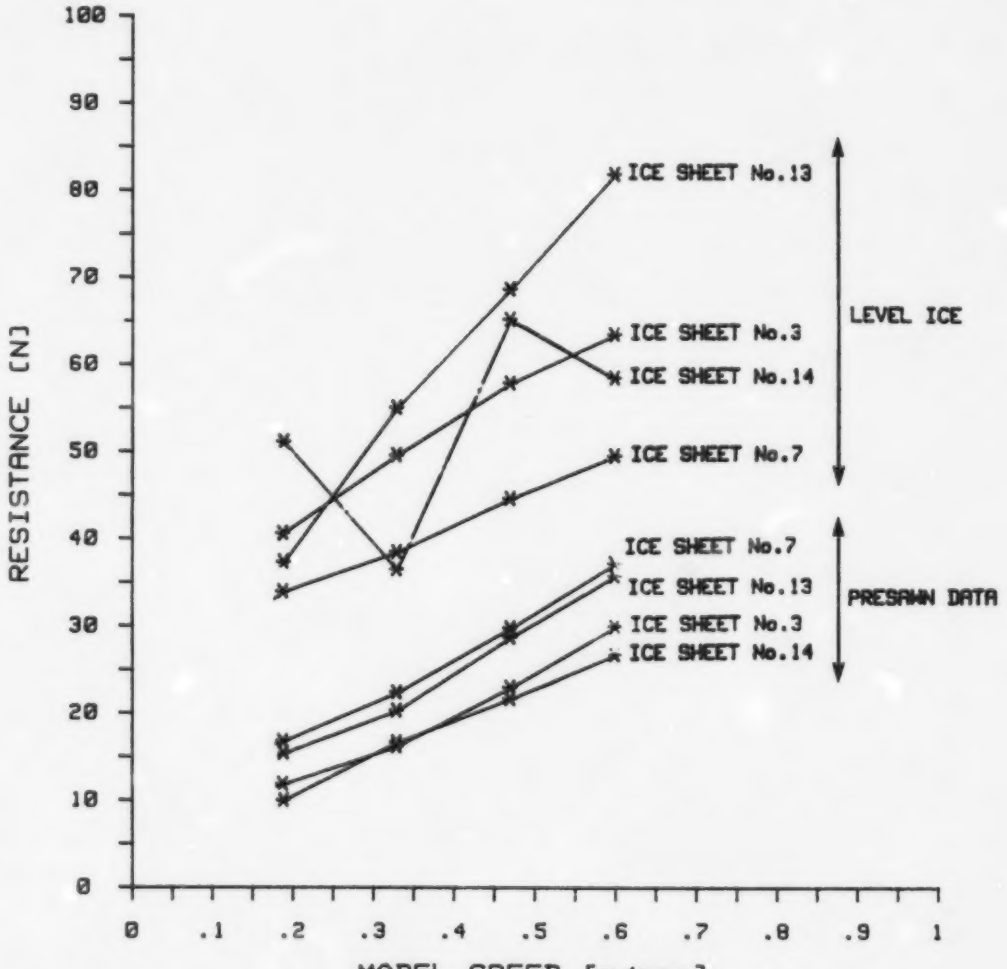
Midbody test program ; Ice sheet #14
. ; Melville bow - 0.4 x Midbody
Data corrected for ice thickness and strength
Target ice thickness = 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06

MELVILLE SHIPPING LTD

FIGURE C22

RESISTANCE vs SPEED FOR THE MELVILLE BOW OVER A RANGE OF DIFFERENT MODEL LENGTHS

(MELVILLE BOW)

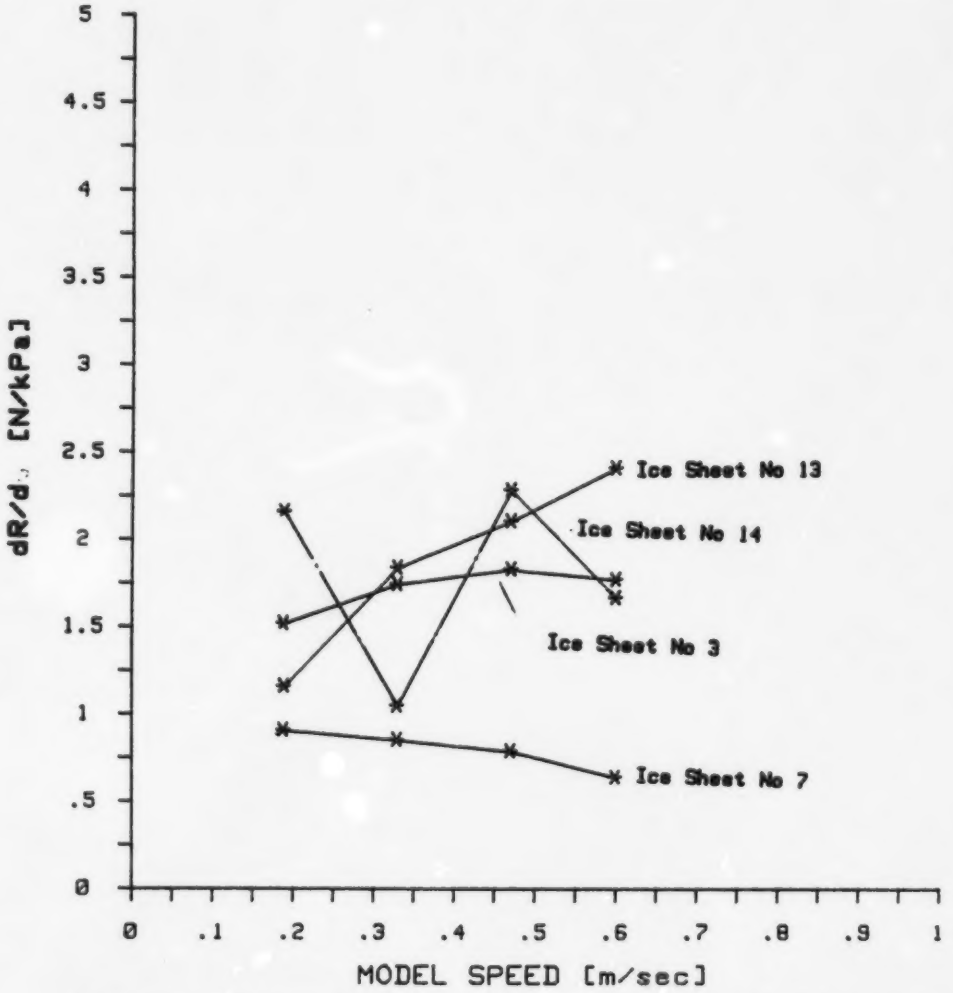


Midbody test program ; Ice sheet #3 #7 #13 and #14
Data corrected for thickness and strength
Target ice thickness = 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06

MELVILLE SHIPPING LTD

FIGURE C23

COMPARISON BETWEEN THE RATE OF CHANGE OF RESISTANCE OVER A RANGE OF MODEL LENGTHS



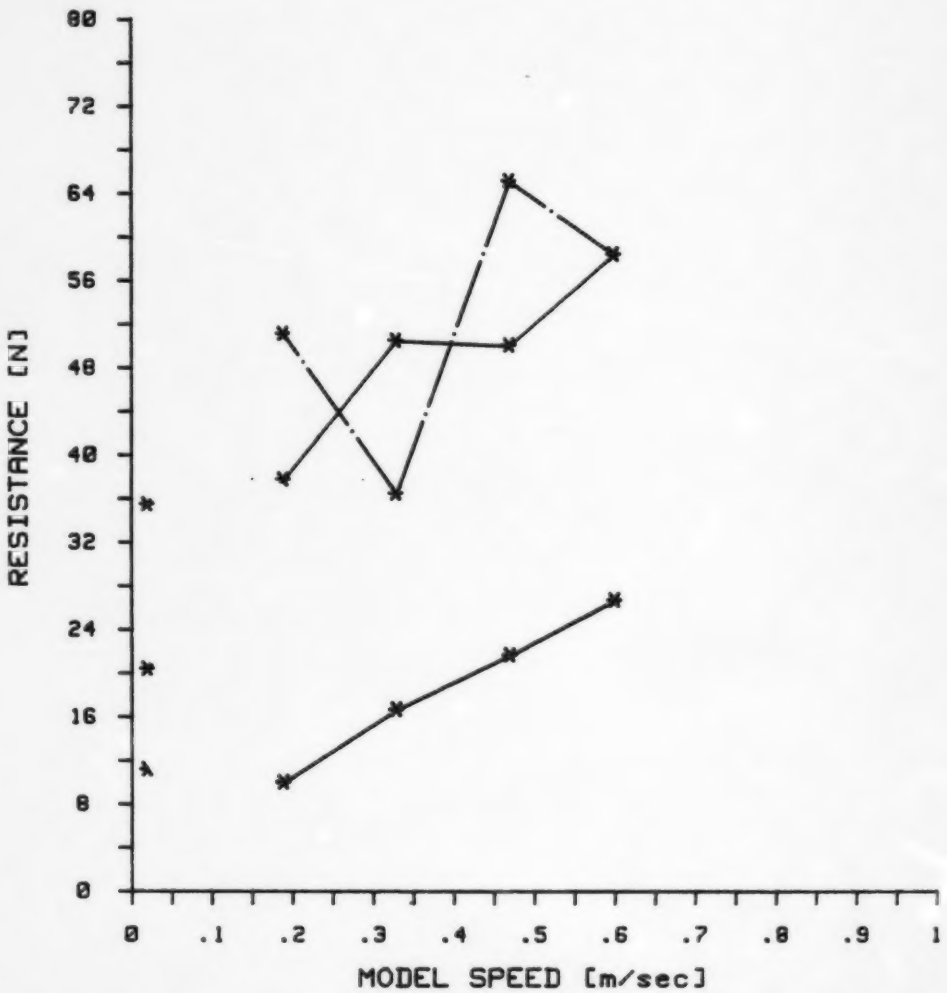
Midbody test program ; Ice sheet #3 #7 #13 and #14
Data corrected for thickness and strength
Target ice thickness = 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06

MELVILLE SHIPPING LTD

FIGURE C24

COMPARISON BETWEEN PRE-SAWN AND LEVEL ICE RESISTANCE BEFORE AND AFTER CORRECTION

(MELVILLE BOW)



Midbody test program ; Ice sheet #14
Data corrected for ice thickness and strength
Target ice thickness = 30 mm
Target ice strength = 19 kPa
Friction coefficient = 0.06

higher low speed resistance. Although this low speed test has not been examined in great detail in the overall tests analysis it was elected to adjust this particular low low speed data point to the average of the other three other ice sheets. This is considered to be justified based on the results of the other ice sheets and the intuitive concept that, at very low speeds the resistance will be independent of the ship length.

Figure C23 presents the rate of change of resistance and strength and clearly there is some irregularity in the data points. Unfortunately there is no substantial evidence for correcting this data in any particular fashion, however, based on experience and the trends identified in the remaining test series, the 0.47 m/sec data point was adjusted by taking the average value obtained from two different procedures.

The first method was to interpolate between the 0.6 and 0.33 m/sec data points on Figure C23. This results in a rate of change of resistance with strength, which in association with the presawn resistance, can be used to calculate the resistance at 19 kPa. The second method was extrapolate down from the 0.6 m/sec value based on the average rate of change of resistance and speed from ice sheets #3 and #7 (Figure C20). The 0.188 m/sec data point was adjusted using the same procedure as the 0.47 m/sec point, using the average rate of change of resistance with strength between the data from ice sheets #3 and #13.

The corrected data set is shown in Figure C24 as Resistance vs Speed. The multiple corrections to this particular ice sheet result in a lower confidence level in the resistance of the model in this condition and this is reflected in the subsequent analysis.

APPENDIX D

ICE SHEET PROPERTIES

The following tables and summary table present the ice sheet data for each of the tests conducted in the program. The summary table presents the crushing, flexural and fracture toughness values corrected for test time.

TABLE D.1

ICE SHEET PROPERTIES

TEST	σ_c [kPa] # of samples	σ_f [kPa] # of samples	h [mm] # of samples	E/σ		Klc	σ_f/Klc
1	97.1 ± 32, 17	22.9 ± 4.7, 46	51.7 ± 0.9, 66	1,775 (σ_f = 5)	76 min. before test	3.75	5.45
2	41.6 ± 8.8, 15	13.8 ± 3, 40	40.7 ± 0.7, 66	1,202 (σ_f = 35)	60 min. before test	2.05	7.30
3	29.9 ± 4.6, 16	14.6 ± 3.6, 44	30.5 ± 0.7, 66	913 (σ_f = 26)	52 min. before test	2.20	8.45
4	90.2 ± 26.7, 16	19.9 ± 4.1, 45	50.7 ± 0.8, 66	1,775 (σ_f = 49)	56 min. before test	3.50	5.40
5	41.2 ± 8.3, 12	23.9 ± 4.5, 48	31.0 ± 0.4, 66	727 (σ_f = 27)	63 min. before test	3.00	7.70
6	38.3 ± 9, 12	19.5 ± 4, 48	31.1 ± 0.4, 66	744 (σ_f = 26)	66 min. before test	3.40	7.20
7	35.5 ± 6.0	19.7 ± 5.2	30.1 ± 0.8, -	645 (σ_f = 26)	64 min. before test	2.30	10.60
8	34.9 ± 8.5	19.7 ± 4.6	30.0 ± 0.7, -	529 (σ_f = 24)	62 min. before test	1.30	17.30
9	22.69 ± 7.39, 16	16.85 ± 4.04, 46	30.8 ± 0.9, 66	746 (σ_f = 26)	50 min. before test	1.60	14.50
10	33.9 ± 8.6, 16	18.7 ± 4.1, 45	30.2 ± 0.8, 66	706 (σ_f = 25)	57 min. before test	1.00	17.80
11	30.5 ± 5.6, 12	20.0 ± 3.2, 47	29.9 ± 0.6, 66	593 (σ_f = 25)	80 min. before test	2.40	9.90
12	37.2 ± 8.0, 16	19.8 ± 4.2, 47	30.0 ± 0.8, 64	606 (σ_f = 25)	65 min. before test	3.20	7.10
13	34.0 ± 4.3, 15	18.9 ± 3.2, 48	29.3 ± 0.5, 66	734 (σ_f = 26)	84 min. before test	2.25	9.90
14	30.8 ± 4.7, 16	18.3 ± 4.4, 47	30.2 ± 0.6, 66	501 (σ_f = 24)	66 min. before test	2.70	9.55

APPENDIX E

MODEL CONDITION

Model Condition

The model condition, defined by its metacentric height and displacement are represented by its transverse metacentre and the roll and pitch period.

The model condition was selected after a review of the actual ships loading conditions shown in Table E.1.

The resultant, as measured metacentric height, roll and pitch periods are presented in Table E.2.

TABLE E.1

M.V. ARCTIC LOADING CONDITIONS

Condition		
1. Full homogenious cargo	100% Cons	GM (solid) = 1.112 GM (fluid) = 0.997
2. Full homogenious cargo	10% Cons	GM (solid) = 1.463 GM (fluid) = 1.421
3. Full ore concentrates	100% Cons	GM (solid) = 2.031 GM (fluid) = 1.948
4. Full ore concentrates	10% Cons	GM (solid) = 2.212 GM (fluid) = 2.101
5. Crude oil	100% Cons	GM (solid) = 1.473 GM (fluid) = 1.147
6. Crude oil	14% Cons	GM (solid) = 1.000 GM (fluid) = 0.708
7. Diesel oil	100% Cons	GM (solid) = 1.780 GM (fluid) = 1.355
8. Diesel oil	14% Cons	GM (solid) = 0.993 GM (fluid) = 0.704

TABLE E.2

TRANSVERSE AND LONGITUDINAL PERIODS

		PERIODS		
		GM	ROLL	PITCH
Tests 1 - 3	Existing Ship	0.0530	2.55	1.50
Test 4	High ∇ bow & midbody Existing length. Melville	0.0520	2.55	1.50
Test 5	High ∇ bow Short ship. Melville	0.0477	2.78	1.88
Test 6	High ∇ bow Short ship. Original	0.0498	2.40	1.82
Test 7	Meduium ∇ Short ship. Melville	0.0540	2.55	1.70
Test 8	Low ∇ Short ship. Melville	0.0470	2.66	1.38
Test 9	Low ∇ Short ship. Original	0.0490	2.54	1.74
Test 10	Medium ∇ Short ship. Original	0.0520	2.28	1.80
Test 11	Medium bow & midbody Existing length. Old bow	0.0519	2.55	1.50
Test 12	Medium bow & midbody Long ship. Old bow	0.0486	2.72	1.50
Test 13	Medium bow & midbody Long ship. Melville	0.0516	2.602	1.52
Test 14	Medium bow & midbody 0.5 x midbody. Melville bow	0.0493	2.60	1.60

APPENDIX F

MODEL TEST DATA

The following tables present the complete set of data from the midbody test program.

Table F.1: presents the as measured data with no modifications or adjustments.

Table F.2: presents the data with the conventional data adjustments for small variations in measured thickness and strength.

Table F.3: presents the data with the conventional data adjustments together with the modifications resulting from the detailed analysis described in Appendix C.

The data is extracted from Melville's standard model test analysis program: the first four columns define the ice sheet number, measured ice thickness, strength and model speed. The fifth column presents the resistance data and includes any corrections that may have been applied. Any correction applied is shown in the sixth column. The seventh column is the model identifier used in the program. The model identifier defines the friction coefficient used on the bow, midbody and stern, together with the type of bow, length of midbody and model ice thickness.

For example 0.06 MB/0.06 PM 1.7/S/30 designates respectively: a 0.06 friction coefficient on the Melville Bow (MB), the Original bow is designated OB; a 0.06 friction coefficient on the Parallel Midbody (PM), equal to 1.7 times the base case length; a stern (S), which was constant and hence does not have any other designation, and; tests completed in 30 mm ice.

TABLE F.1

MIDBODY PROGRAM OF TESTS
- AS MEASURED DATA -

SET	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	TOTAL RESISTANCE [N]	CORRECTION VALUE [N]	TEST DESCRIPTION
	51.40	0.0	.020	22.000	0.000	.06MB/.06PB/S/50
	51.40	0.0	.188	31.000	0.000	.06MB/.06PB/S/50
	51.70	0.0	.329	44.500	0.000	.06MB/.06PB/S/50
	52.50	0.0	.470	49.700	0.000	.06MB/.06PB/S/50
	51.40	0.0	.600	54.200	0.000	.06MB/.06PB/S/50
	51.40	29.6	.020	98.600	0.000	.06MB/.06PB/S/50
	51.40	21.8	.188	85.700	0.000	.06MB/.06PB/S/50
	51.70	22.4	.329	121.300	0.000	.06MB/.06PB/S/50
	52.50	18.6	.470	113.100	0.000	.06MB/.06PB/S/50
	51.40	28.6	.600	162.700	0.000	.06MB/.06PB/S/50
	40.50	0.0	.020	13.700	0.000	.06MB/.06PB/S/40
	40.60	0.0	.188	18.200	0.000	.06MB/.06PB/S/40
	40.50	0.0	.329	26.100	0.000	.06MB/.06PB/S/40
	41.40	0.0	.470	35.700	0.000	.06MB/.06PB/S/40
	40.50	0.0	.600	39.600	0.000	.06MB/.06PB/S/40
	40.50	17.5	.020	39.800	0.000	.06MB/.06PB/S/40
	40.60	10.9	.188	54.000	0.000	.06MB/.06PB/S/40
	40.50	13.6	.329	73.200	0.000	.06MB/.06PB/S/40
	41.40	13.4	.470	83.600	0.000	.06MB/.06PB/S/40
	40.50	17.5	.600	76.300	0.000	.06MB/.06PB/S/40
	29.90	0.0	.020	7.100	0.000	.06MB/.06PB/S/30
	30.70	0.0	.188	12.400	0.000	.06MB/.06PB/S/30
	30.70	0.0	.329	17.000	0.000	.06MB/.06PB/S/30
	30.70	0.0	.470	23.700	0.000	.06MB/.06PB/S/30
	29.90	0.0	.600	29.700	0.000	.06MB/.06PB/S/30
	29.80	17.2	.020	17.600	0.000	.06MB/.06PB/S/30
	30.70	11.1	.188	35.400	0.000	.06MB/.06PB/S/30
	30.70	10.5	.329	41.400	0.000	.06MB/.06PB/S/30
	30.70	16.8	.470	53.600	0.000	.06MB/.06PB/S/30
	29.90	17.2	.600	59.700	0.000	.06MB/.06PB/S/30
	50.40	0.0	.020	66.700	0.000	.33MB/.33PB/S/40
	50.60	0.0	.188	61.900	0.000	.33MB/.33PB/S/40
	50.50	0.0	.329	75.200	0.000	.33MB/.33PB/S/40
	51.30	0.0	.470	86.200	0.000	.33MB/.33PB/S/40
	50.40	0.0	.600	105.700	0.000	.33MB/.33PB/S/40
	50.40	25.1	.020	138.600	0.000	.33MB/.33PB/S/40

TABLE F.1(cont.)

MIDBODY PROGRAM OF TESTS
- AS MEASURED DATA -

SHEET #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	TOTAL RESISTANCE [N]	CORRECTION VALUE [N]	MODEL DESCRIPTION
4	50.60	15.8	.188	117.900	0.000	.33MB/.33PB/S/50
4	50.50	20.1	.329	187.200	0.000	.33MB/.33PB/S/50
4	51.30	18.6	.470	229.000	0.000	.33MB/.33PB/S/50
4	50.40	25.1	.600	349.300	0.000	.33MB/.33PB/S/50
5	30.90	0.0	.020	17.400	0.000	.33MB/S/30
5	31.10	0.0	.188	26.000	0.000	.33MB/S/30
5	31.10	0.0	.329	32.400	0.000	.33MB/S/30
5	31.10	0.0	.470	42.600	0.000	.33MB/S/30
5	30.90	0.0	.600	51.900	0.000	.33MB/S/30
5	30.90	28.4	.020	77.900	0.000	.33MB/S/30
5	31.10	18.9	.188	67.300	0.000	.33MB/S/30
5	31.10	22.4	.329	78.400	0.000	.33MB/S/30
5	31.10	25.7	.470	100.600	0.000	.33MB/S/30
5	30.90	28.4	.600	111.400	0.000	.33MB/S/30
6	31.20	0.0	.020	14.700	0.000	.330B/S/30
6	31.10	0.0	.188	17.800	0.000	.330B/S/30
6	31.10	0.0	.329	22.900	0.000	.330B/S/30
6	31.10	0.0	.470	30.600	0.000	.330B/S/30
6	31.20	0.0	.600	37.000	0.000	.330B/S/30
6	31.20	22.5	.020	35.000	0.000	.330B/S/30
7	31.10	15.5	.188	58.800	0.000	.330B/S/30
7	31.10	18.4	.329	69.000	0.000	.330B/S/30
7	31.10	21.3	.470	85.400	0.000	.330B/S/30
7	31.20	22.5	.600	92.800	0.000	.330B/S/30
7	29.40	0.0	.020	11.300	0.000	.06MB/S/30
7	30.10	0.0	.188	16.800	0.000	.06MB/S/30
7	30.30	0.0	.329	22.800	0.000	.06MB/S/30
7	30.60	0.0	.470	30.600	0.000	.06MB/S/30
7	29.40	0.0	.600	36.200	0.000	.06MB/S/30
7	29.40	23.4	.020	21.400	0.000	.06MB/S/30
7	30.10	13.0	.188	31.500	0.000	.06MB/S/30
7	30.30	20.8	.329	40.700	0.000	.06MB/S/30
7	30.60	21.5	.470	48.000	0.000	.05MB/S/30
7	29.40	23.4	.600	49.500	0.000	.06MB/S/30
8	29.30	0.0	.020	4.700	0.000	.004MB/S/30

TABLE F.1 (cont.)

MIDBODY PROGRAM OF TESTS
- AS MEASURED DATA -

SHEET #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	TOTAL RESISTANCE [N]	CORRECTION VALUE [N]	MODEL DESCRIPTION
8	30.00	0.0	.188	6.400	0.000	.004MB/S/30
8	30.40	0.0	.329	9.300	0.000	.004MB/S/30
8	30.20	0.0	.470	14.200	0.000	.004MB/S/30
8	29.30	0.0	.600	20.500	0.000	.004MB/S/30
8	29.30	22.9	.020	12.400	0.000	.004MB/S/30
8	30.00	20.4	.188	21.400	0.000	.004MB/S/30
8	30.40	20.2	.329	23.300	0.000	.004MB/S/30
8	30.20	14.8	.470	26.700	0.000	.004MB/S/30
8	29.30	22.9	.600	30.100	0.000	.004MB/S/30
8	30.00	0.0	.020	6.500	0.000	.0040B/S/30
9	30.90	0.0	.188	10.200	0.000	.0040B/S/30
9	31.00	0.0	.329	13.900	0.000	.0040B/S/30
9	31.30	0.0	.470	17.400	0.000	.0040B/S/30
9	30.00	0.0	.600	21.900	0.000	.0040B/S/30
9	30.00	20.2	.020	14.500	0.000	.0040B/S/30
8	30.90	12.9	.188	25.800	0.000	.0040B/S/30
9	31.00	14.5	.329	34.000	0.000	.0040B/S/30
9	31.30	19.1	.470	46.700	0.000	.0040B/S/30
9	30.00	20.2	.600	47.900	0.000	.0040B/S/30
10	29.60	0.0	.020	25.100	0.000	.060B/S/30
10	30.30	0.0	.188	30.140	0.000	.060B/S/30
10	30.20	0.0	.329	33.100	0.000	.060B/S/30
10	30.90	0.0	.470	42.300	0.000	.060B/S/30
10	29.60	0.0	.600	46.200	0.000	.060B/S/30
10	29.60	19.9	.020	39.100	0.000	.060B/S/30
10	30.30	13.0	.188	81.600	0.000	.060B/S/30
10	30.20	22.8	.329	85.400	0.000	.060B/S/30
10	30.90	17.7	.470	114.900	0.000	.060B/S/30
10	29.60	19.9	.600	102.200	0.000	.060B/S/30
11	29.40	0.0	.020	15.200	0.000	.060B/.06PB/S/30
11	30.20	0.0	.189	32.900	0.000	.060B/.06PB/S/30
11	30.20	0.0	.329	42.800	0.000	.060B/.06PB/S/30
11	30.10	0.0	.470	45.600	0.000	.060B/.06PB/S/30
11	29.40	0.0	.600	47.600	0.000	.060B/.06PB/S/30
11	29.40	19.9	.020	58.400	0.000	.060B/.06PB/S/30

TABLE F.1 (cont.)

MIDBODY PROGRAM OF TESTS
- AS MEASURED DATA -

SHEET #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	TOTAL RESISTANCE [N]	CORRECTION VALUE [N]	MODEL DESCRIPTION
11	30.20	18.0	.189	103.100	0.000	.060B/.06PB/S/30
11	30.20	19.2	.329	103.500	0.000	.060B/.06PB/S/30
11	30.10	23.2	.470	133.900	0.000	.060B/.06PB/S/30
11	29.40	19.8	.600	119.500	0.000	.060B/.06PB/S/30
12	29.40	0.0	.020	20.700	0.000	.060B/.06PB1.7/S/30
12	30.20	0.0	.189	30.400	0.000	.060B/.06PB1.7/S/30
12	30.00	0.0	.329	35.400	0.000	.060B/.06PB1.7/S/30
12	30.60	0.0	.470	42.000	0.000	.060B/.06PB1.7/S/30
12	29.40	0.0	.600	47.000	0.000	.060B/.06PB1.7/S/30
12	29.40	24.9	.020	35.400	0.000	.060B/.06PB1.7/S/30
12	30.20	15.7	.189	64.200	0.000	.060B/.06PB1.7/S/30
12	30.00	18.9	.329	89.100	0.000	.060B/.06PB1.7/S/30
12	30.60	19.7	.470	110.500	0.000	.060B/.06PB1.7/S/30
12	29.40	24.9	.600	107.500	0.000	.060B/.06PB1.7/S/30
13	29.00	0.0	.020	9.200	0.000	.06MB/.06PB1.7/S/30
13	29.40	0.0	.189	14.700	0.000	.06MB/.06PB1.7/S/30
13	29.40	0.0	.329	19.300	0.000	.06MB/.06PB1.7/S/30
13	29.50	0.0	.470	27.900	0.000	.06MB/.06PB1.7/S/30
13	29.00	0.0	.600	34.300	0.000	.06MB/.06PB1.7/S/30
13	29.00	20.5	.020	16.600	0.000	.06MB/.06PB1.7/S/30
13	29.40	15.9	.189	32.700	0.000	.06MB/.06PB1.7/S/30
13	29.40	17.6	.329	50.500	0.000	.06MB/.06PB1.7/S/30
13	29.50	21.4	.470	56.600	0.000	.06MB/.06PB1.7/S/30
13	29.00	20.5	.600	78.600	0.000	.06MB/.06PB1.7/S/30
14	29.80	0.0	.020	10.900	0.000	.06MB/.06PB.5/S/30
14	30.50	0.0	.189	10.300	0.000	.06MB/.06PB.5/S/30
14	30.40	0.0	.329	17.100	0.000	.06MB/.06PB.5/S/30
14	30.30	0.0	.470	21.900	0.000	.06MB/.06PB.5/S/30
14	29.80	0.0	.600	26.400	0.000	.06MB/.06PB.5/S/30
14	29.80	23.2	.020	38.800	0.000	.06MB/.06PB.5/S/30
14	30.50	16.8	.189	47.800	0.000	.06MB/.06PB.5/S/30
14	30.40	19.1	.329	37.900	0.000	.06MB/.06PB.5/S/30
14	30.30	13.4	.470	52.900	0.000	.06MB/.06PB.5/S/30
14	29.80	23.2	.600	64.100	0.000	.06MB/.06PB.5/S/30

TABLE F.2

MIDBODY PROGRAM OF TESTS
- DATA CORRECTED WITH STANDARD PROCEDURES -

	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	TOTAL RESISTANCE [N]	CORRECTION VALUE [N]	MODEL DESCRIPTION
1	51.40	0.0	.020	21.030	-.970	.06MB/.06PB/S/50
1	51.40	0.0	.188	29.742	-1.258	.06MB/.06PB/S/50
1	51.70	0.0	.329	42.274	-2.226	.06MB/.06PB/S/50
1	52.50	0.0	.470	46.718	-2.982	.06MB/.06PB/S/50
1	51.40	0.0	.600	52.605	-1.595	.06MB/.06PB/S/50
1	51.40	28.6	.020	67.609	-30.991	.06MB/.06PB/S/50
1	51.40	21.8	.188	76.076	-10.624	.06MB/.06PB/S/50
1	51.70	22.4	.329	103.175	-18.125	.06MB/.06PB/S/50
1	52.50	18.6	.470	107.640	-5.460	.06MB/.06PB/S/50
1	51.40	28.6	.600	119.573	-43.127	.06MB/.06PB/S/50
2	40.50	0.0	.020	13.031	-.669	.06MB/.06PB/S/40
2	40.60	0.0	.188	17.409	-.791	.06MB/.06PB/S/40
2	40.50	0.0	.329	25.095	-1.005	.06MB/.06PB/S/40
2	41.40	0.0	.470	33.185	-2.515	.06MB/.06PB/S/40
2	40.50	0.0	.600	38.840	-.760	.06MB/.06PB/S/40
2	40.50	17.5	.020	37.757	-2.043	.06MB/.06PB/S/40
2	40.60	10.9	.188	78.335	24.335	.06MB/.06PB/S/40
2	40.50	13.6	.329	88.538	15.338	.06MB/.06PB/S/40
2	41.40	13.4	.470	97.658	14.058	.06MB/.06PB/S/40
2	40.50	17.5	.600	76.384	.084	.06MB/.06PB/S/40
3	29.90	0.0	.020	7.169	.069	.06MB/.06PB/S/30
3	30.70	0.0	.188	11.771	-.629	.06MB/.06PB/S/30
3	30.70	0.0	.329	16.083	-.917	.06MB/.06PB/S/30
3	30.70	0.0	.470	22.865	-.835	.06MB/.06PB/S/30
3	29.90	0.0	.600	29.814	.114	.06MB/.06PB/S/30
3	29.90	17.2	.020	18.999	1.469	.06MB/.06PB/S/30
3	30.70	11.1	.188	50.035	14.635	.06MB/.06PB/S/30
3	30.70	13.5	.329	48.677	7.277	.06MB/.06PB/S/30
3	30.70	15.8	.470	57.745	4.145	.06MB/.06PB/S/30
3	29.90	17.2	.600	63.319	3.619	.06MB/.06PB/S/30
4	50.40	0.0	.020	65.860	-.840	.33MB/.33PB/S/50
4	50.60	0.0	.188	60.725	-1.075	.33MB/.33PB/S/50
4	50.50	0.0	.329	74.094	-1.106	.33MB/.33PB/S/50
4	51.30	0.0	.470	83.511	-2.689	.33MB/.33PB/S/50
4	50.40	0.0	.600	104.811	-.889	.33MB/.33PB/S/50
4	50.40	25.1	.020	158.080	-32.510	.33MB/.33PB/S/50

TABLE F.2 (cont.)

MIDBODY PROGRAM OF TESTS
- DATA CORRECTED WITH STANDARD PROCEDURES -

SHEET #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	TOTAL RESISTANCE [N]	CORRECTION VALUE [N]	MODEL DESCRIPTION
4	50.60	15.8	.188	127.240	9.340	.33MB/.33PB/S/50
4	50.50	20.1	.329	178.135	-9.065	.33MB/.33PB/S/50
4	51.30	18.6	.470	224.887	-4.113	.33MB/.33PB/S/50
4	50.40	25.1	.600	285.984	-63.316	.33MB/.33PB/S/50
5	30.90	0.0	.020	15.871	-1.529	.33MB/S/30
5	31.10	0.0	.188	23.928	-2.072	.33MB/S/30
5	31.10	0.0	.329	29.655	-2.745	.33MB/S/30
5	31.10	0.0	.470	40.242	-2.358	.33MB/S/30
5	30.90	0.0	.600	50.108	-1.792	.33MB/S/30
5	30.90	28.4	.020	42.795	-35.105	.33MB/S/30
5	31.10	18.9	.188	62.336	-4.964	.33MB/S/30
5	31.10	22.4	.329	63.492	-14.908	.33MB/S/30
5	31.10	25.7	.470	79.844	-20.756	.33MB/S/30
5	30.90	28.4	.600	83.661	-27.739	.33MB/S/30
6	31.20	0.0	.020	12.978	-1.722	.330B/S/30
6	31.10	0.0	.188	16.381	-1.419	.330B/S/30
6	31.10	0.0	.329	20.960	-1.940	.330B/S/30
6	31.10	0.0	.470	28.906	-1.694	.330B/S/30
6	31.20	0.0	.600	35.296	-1.704	.330B/S/30
6	31.20	22.5	.020	22.808	-12.192	.330B/S/30
6	31.10	15.5	.188	63.530	4.730	.330B/S/30
6	31.10	18.4	.329	63.528	-5.472	.330B/S/30
6	31.10	21.3	.470	74.699	-10.701	.330B/S/30
6	31.20	22.5	.600	75.184	-17.616	.330B/S/30
7	29.40	0.0	.020	12.491	.691	.06MB/S/30
7	30.10	0.0	.188	16.678	-.122	.06MB/S/30
7	30.30	0.0	.329	22.273	-.527	.06MB/S/30
7	30.60	0.0	.470	29.676	-.924	.06MB/S/30
7	29.40	0.0	.600	37.033	.833	.06MB/S/30
7	29.40	23.4	.020	22.357	.957	.06MB/S/30
7	30.10	13.0	.188	38.064	6.564	.06MB/S/30
7	30.30	20.8	.329	38.029	-2.671	.06MB/S/30
7	30.60	21.5	.470	44.510	-3.490	.06MB/S/30
7	29.40	23.4	.600	49.382	-.118	.06MB/S/30
[illegible]	29.30	0.0	.020	8.021	.321	.06MB/S/30

TABLE F.2 (cont.)

MIDBODY PROGRAM OF TESTS
- DATA CORRECTED WITH STANDARD PROCEDURES -

SHEET #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	TOTAL RESISTANCE [N]	CORRECTION VALUE [N]	MODEL DESCRIPTION
8	30.00	0.0	.188	6.400	0.000	.004MB/S/30
8	30.40	0.0	.329	9.013	-.287	.004MB/S/30
8	30.20	0.0	.470	14.057	-.143	.004MB/S/30
8	29.30	0.0	.600	21.051	.551	.004MB/S/30
8	29.30	22.9	.020	12.956	.556	.004MB/S/30
8	30.00	20.4	.188	20.371	-1.029	.004MB/S/30
8	30.40	20.2	.329	21.612	-1.688	.004MB/S/30
8	30.20	14.9	.470	29.868	3.168	.004MB/S/30
8	29.30	22.9	.600	30.156	.056	.004MB/S/30
9	30.00	0.0	.020	6.500	0.000	.0040B/S/30
9	30.90	0.0	.188	9.535	-.665	.0040B/S/30
9	31.00	0.0	.329	12.829	-1.071	.0040B/S/30
9	31.30	0.0	.470	16.262	-1.138	.0040B/S/30
9	30.00	0.0	.600	21.900	0.000	.0040B/S/30
9	30.00	20.2	.020	14.025	-.475	.0040B/S/30
9	30.90	12.9	.188	31.551	5.751	.0040B/S/30
9	31.00	14.5	.329	37.113	3.113	.0040B/S/30
9	31.30	19.1	.470	43.455	-3.245	.0040B/S/30
9	30.00	20.2	.600	46.355	-1.545	.0040B/S/30
10	29.60	0.0	.020	26.080	.980	.060B/S/30
10	30.30	0.0	.188	29.485	-.655	.060B/S/30
10	30.20	0.0	.329	32.590	-.510	.060B/S/30
10	30.90	0.0	.470	40.384	-1.916	.060B/S/30
10	29.60	0.0	.600	46.909	.709	.060B/S/30
10	29.60	19.9	.020	41.831	2.731	.060B/S/30
10	30.30	13.0	.188	103.637	22.037	.060B/S/30
10	30.20	22.8	.329	75.114	-10.286	.060B/S/30
10	30.90	17.7	.470	114.966	.066	.060B/S/30
10	29.60	19.9	.600	102.948	.748	.060B/S/30
11	29.40	0.0	.020	16.090	.890	.060B/.06PB/S/30
11	30.20	0.0	.189	32.423	-.477	.060B/.06PB/S/30
11	30.20	0.0	.329	42.141	-.659	.060B/.06PB/S/30
11	30.10	0.0	.470	45.371	-.229	.060B/.06PB/S/30
11	29.40	0.0	.600	48.696	1.096	.060B/.06PB/S/30
11	28.40	19.3	.020	75.278	6.878	.060B/.06PB/S/30

TABLE F.2 (cont.)

MIDBODY PROGRAM OF TESTS
- DATA CORRECTED WITH STANDARD PROCEDURES -

SHEET #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	TOTAL RESISTANCE [N]	CORRECTION VALUE [N]	MODEL DESCRIPTION
11	30.20	18.0	.189	105.556	2.456	.060B/.06PB/S/30
11	30.20	19.2	.329	100.965	-2.535	.060B/.06PB/S/30
11	30.10	23.2	.470	117.233	-16.667	.060B/.06PB/S/30
11	29.40	19.8	.600	122.349	2.849	.060B/.06PB/S/30
12	29.40	0.0	.020	21.912	1.212	.060B/.06PB1.7/S/30
12	30.20	0.0	.189	29.959	-.441	.060B/.06PB1.7/S/30
12	30.00	0.0	.329	35.400	0.000	.060B/.06PB1.7/S/30
12	30.60	0.0	.470	40.732	-1.268	.060B/.06PB1.7/S/30
12	29.40	0.0	.600	48.082	1.082	.060B/.06PB1.7/S/30
12	29.40	24.9	.020	36.486	1.086	.060B/.06PB1.7/S/30
12	30.20	15.7	.189	70.406	6.206	.060B/.06PB1.7/S/30
12	30.00	18.9	.329	89.384	.284	.060B/.06PB1.7/S/30
12	30.60	19.7	.470	104.690	-5.810	.060B/.06PB1.7/S/30
12	29.40	24.9	.600	98.341	-9.159	.060B/.06PB1.7/S/30
13	29.00	0.0	.020	10.098	.898	.06MB/.06PB1.7/S/30
13	29.40	0.0	.189	15.339	.639	.06MB/.06PB1.7/S/30
13	29.40	0.0	.329	20.192	.892	.06MB/.06PB1.7/S/30
13	29.50	0.0	.470	28.602	.702	.06MB/.06PB1.7/S/30
13	29.00	0.0	.600	35.616	1.316	.06MB/.06PB1.7/S/30
13	29.00	20.5	.020	19.629	3.029	.06MB/.06PB1.7/S/30
13	29.40	15.9	.189	37.583	4.883	.06MB/.06PB1.7/S/30
13	29.40	17.6	.329	55.766	5.266	.06MB/.06PB1.7/S/30
13	29.50	21.4	.470	54.822	-1.778	.06MB/.06PB1.7/S/30
13	29.00	20.5	.600	81.666	3.066	.06MB/.06PB1.7/S/30
14	29.80	0.0	.020	11.113	.213	.06MB/.06PB.5/S/30
14	30.50	0.0	.189	9.927	-.373	.06MB/.06PB.5/S/30
14	30.40	0.0	.329	16.573	-.527	.06MB/.06PB.5/S/30
14	30.30	0.0	.470	21.569	-.331	.06MB/.06PB.5/S/30
14	29.80	0.0	.600	26.603	.203	.06MB/.06PB.5/S/30
14	29.80	23.2	.020	35.418	-3.382	.06MB/.06PB.5/S/30
14	30.50	16.8	.189	51.038	3.238	.06MB/.06PB.5/S/30
14	30.40	19.1	.329	36.398	-1.502	.06MB/.06PB.5/S/30
14	30.30	13.4	.470	65.047	12.147	.06MB/.06PB.5/S/30
14	29.80	23.2	.600	58.304	-5.796	.06MB/.06PB.5/S/30

TABLE F.3

MIDBODY PROGRAM OF TESTS
- DATA CORRECTED IN ACCORDANCE WITH APPENDIX C MODIFICATIONS -

LT	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	TOTAL RESISTANCE [N]	CORRECTION VALUE [N]	MODEL DESCRIPTION
1	51.40	0.0	.020	21.030	-.970	.06MB/.06PB/S/50
1	51.40	0.0	.188	29.742	-1.258	.06MB/.06PB/S/50
1	51.70	0.0	.329	42.274	-2.226	.06MB/.06PB/S/50
1	52.50	0.0	.470	46.718	-2.982	.06MB/.06PB/S/50
1	51.40	0.0	.600	52.605	-1.595	.06MB/.06PB/S/50
1	51.40	28.6	.020	67.609	-30.991	.06MB/.06PB/S/50
1	51.40	21.8	.188	76.526	-10.174	.06MB/.06PB/S/50
1	50.00	19.0	.329	92.500	0.000	.06MB/.06PB/S/50
1	52.50	18.6	.470	107.640	-5.460	.06MB/.06PB/S/50
1	51.40	28.6	.600	119.573	-43.127	.06MB/.06PB/S/50
2	40.50	0.0	.020	13.031	-.669	.06MB/.06PB/S/40
2	40.60	0.0	.188	17.409	-.791	.06MB/.06PB/S/40
2	40.50	0.0	.329	25.095	-1.005	.06MB/.06PB/S/40
2	41.40	0.0	.470	33.185	-2.515	.06MB/.06PB/S/40
2	40.50	0.0	.600	38.840	-.760	.06MB/.06PB/S/40
2	40.50	17.5	.020	37.757	-2.043	.06MB/.06PB/S/40
2	40.60	19.0	.188	58.764	-1.866	.06MB/.06PB/S/40
2	40.50	19.0	.329	71.177	-1.033	.06MB/.06PB/S/40
2	41.40	19.0	.470	80.426	-6.174	.06MB/.06PB/S/40
2	40.50	19.0	.600	90.334	-3.776	.06MB/.06PB/S/40
3	29.90	0.0	.020	7.169	.069	.06MB/.06PB/S/30
3	30.70	0.0	.188	11.771	-.629	.06MB/.06PB/S/30
3	30.70	0.0	.329	16.083	-.917	.06MB/.06PB/S/30
3	30.70	0.0	.470	22.865	-.835	.06MB/.06PB/S/30
3	29.90	0.0	.600	29.814	.114	.06MB/.06PB/S/30
3	29.90	17.2	.020	18.989	1.469	.06MB/.06PB/S/30
3	30.70	19.0	.188	40.540	-1.910	.06MB/.06PB/S/30
3	30.70	13.5	.329	49.487	8.087	.06MB/.06PB/S/30
3	30.70	15.8	.470	57.745	4.145	.06MB/.06PB/S/30
3	29.90	17.2	.600	63.319	3.619	.06MB/.06PB/S/30
4	50.40	0.0	.020	65.860	-.840	.4MB/.4PB/S/50
4	50.60	0.0	.188	60.725	-1.075	.4MB/.4PB/S/50
4	50.50	0.0	.329	74.094	-1.106	.4MB/.4PB/S/50
4	51.30	0.0	.470	83.511	-2.689	.4MB/.4PB/S/50
4	50.40	0.0	.600	104.811	-.989	.4MB/.4PB/S/50
4	50.40	25.1	.020	155.080	-22.610	.4MB/.4PB/S/50

TABLE F.3 (cont.)

MIDBODY PROGRAM OF TESTS
- DATA CORRECTED IN ACCORDANCE WITH APPENDIX C MODIFICATIONS -

SHEET #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	TOTAL RESISTANCE [N]	CORRECTION VALUE [N]	MODEL DESCRIPTION
4	50.60	15.8	.188	127.502	9.602	.4MB/.4PB/S/50
4	50.50	20.1	.329	178.391	-8.809	.4MB/.4PB/S/50
4	51.30	18.6	.470	224.887	-4.113	.4MB/.4PB/S/50
4	50.40	25.1	.600	285.984	-63.316	.4MB/.4PB/S/50
5	30.90	0.0	.020	15.871	-1.529	.4MB/S/30
5	31.10	0.0	.188	23.928	-2.072	.4MB/S/30
5	31.10	0.0	.329	29.355	-2.745	.4MB/S/30
5	31.10	0.0	.470	40.242	-2.358	.4MB/S/30
5	30.90	0.0	.600	50.108	-1.792	.4MB/S/30
5	30.90	28.4	.020	42.795	-35.105	.4MB/S/30
5	31.10	18.9	.188	63.721	-3.579	.4MB/S/30
5	31.10	22.4	.329	65.903	-12.497	.4MB/S/30
5	31.10	25.7	.470	79.844	-20.756	.4MB/S/30
5	30.90	28.4	.600	83.661	-27.739	.4MB/S/30
6	31.20	0.0	.020	12.978	-1.722	.40B/S/30
6	31.10	0.0	.188	16.381	-1.419	.40B/S/30
6	31.10	0.0	.329	20.960	-1.940	.40B/S/30
6	31.10	0.0	.470	28.906	-1.694	.40B/S/30
6	31.20	0.0	.600	35.296	-1.704	.40B/S/30
6	31.20	22.5	.020	22.808	-12.192	.40B/S/30
6	31.10	15.5	.188	64.740	5.940	.40B/S/30
6	31.10	18.4	.329	65.649	-3.351	.40B/S/30
6	31.10	21.3	.470	74.699	-10.701	.40B/S/30
6	31.20	22.5	.600	75.184	-17.616	.40B/S/30
7	29.40	0.0	.020	12.491	.691	.06MB/S/30
7	30.10	0.0	.188	16.678	-.122	.06MB/S/30
7	30.30	0.0	.329	22.273	-.527	.06MB/S/30
7	30.60	0.0	.470	29.676	-.824	.06MB/S/30
7	29.40	0.0	.600	37.033	.833	.06MB/S/30
7	29.40	23.4	.020	22.357	.957	.06MB/S/30
7	30.00	19.0	.188	33.850	0.000	.06MB/S/30
7	30.30	20.8	.329	38.370	-2.330	.06MB/S/30
7	30.60	21.5	.470	44.510	-3.490	.06MB/S/30
7	29.40	23.4	.600	49.382	-.118	.06MB/S/30
8	29.30	0.0	.020	5.021	.321	.004MB/S/30

TABLE F.3 (cont.)

MIDBODY PROGRAM OF TESTS
- DATA CORRECTED IN ACCORDANCE WITH APPENDIX C MODIFICATIONS -

SHEET #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	TOTAL RESISTANCE [N]	CORRECTION VALUE [N]	MODEL DESCRIPTION
8	30.00	0.0	.188	6.400	0.000	.004MB/S/30
8	30.40	0.0	.329	9.013	-.287	.004MB/S/30
8	30.20	0.0	.470	14.057	-.143	.004MB/S/30
8	29.30	0.0	.600	21.051	.551	.004MB/S/30
8	29.30	22.9	.020	12.956	.556	.004MB/S/30
8	30.00	20.4	.188	20.371	-1.029	.004MB/S/30
8	30.40	20.2	.329	21.872	-1.428	.004MB/S/30
8	30.20	14.9	.470	29.868	3.168	.004MB/S/30
8	30.00	19.0	.600	35.920	0.000	.004MB/S/30
9	30.00	0.0	.020	6.500	0.000	.0040B/S/30
9	30.90	0.0	.188	9.535	-.665	.0040B/S/30
9	31.00	0.0	.329	12.829	-1.071	.0040B/S/30
9	31.30	0.0	.470	16.262	-1.138	.0040B/S/30
9	30.00	0.0	.600	21.900	0.000	.0040B/S/30
9	30.00	20.2	.020	14.025	-.475	.0040B/S/30
9	30.90	12.9	.188	31.986	6.186	.0040B/S/30
9	31.00	14.5	.329	38.064	4.064	.0040B/S/30
9	31.30	19.1	.470	43.455	-3.245	.0040B/S/30
9	30.00	20.2	.600	46.355	-1.545	.0040B/S/30
10	29.60	0.0	.020	26.080	.980	.060B/S/30
10	30.30	0.0	.188	29.485	-.655	.060B/S/30
10	30.20	0.0	.329	32.590	-.510	.060B/S/30
10	30.90	0.0	.470	40.384	-1.916	.060B/S/30
10	29.60	0.0	.600	46.909	.709	.060B/S/30
10	29.60	19.9	.020	41.831	2.731	.060B/S/30
10	30.00	19.0	.188	68.510	0.000	.060B/S/30
10	30.20	22.8	.329	75.591	-9.809	.060B/S/30
10	30.00	19.0	.470	89.990	0.000	.060B/S/30
10	29.60	19.9	.600	102.948	.748	.060B/S/30
11	29.40	0.0	.020	16.090	.890	.060B/.06PB/S/30
11	30.20	0.0	.189	32.423	-.477	.060B/.06PB/S/30
11	30.20	0.0	.329	42.141	-.659	.060B/.06PB/S/30
11	30.10	0.0	.470	45.371	-.229	.060B/.06PB/S/30
11	29.40	0.0	.600	48.696	1.096	.060B/.06PB/S/30
11	29.40	19.8	.020	75.078	6.678	.060B/.06PB/S/30

TABLE F.3 (cont.)

MIDBODY PROGRAM OF TESTS
- DATA CORRECTED IN ACCORDANCE WITH APPENDIX C MODIFICATIONS -

SHEET #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	TOTAL RESISTANCE [N]	CORRECTION VALUE [N]	MODEL DESCRIPTION
[illegible]	30.20	18.0	.189	105.942	2.842	.060B/.06PB/S/30
[illegible]	30.20	19.2	.329	101.544	-1.956	.060B/.06PB/S/30
[illegible]	30.10	23.2	.470	117.233	-16.667	.060B/.06PB/S/30
[illegible]	29.40	19.8	.600	122.349	2.849	.060B/.06PB/S/30
12	29.40	0.0	.020	21.912	1.212	.060B/.06PB1.7/S/30
12	30.20	0.0	.189	29.959	-.441	.060B/.06PB1.7/S/30
[illegible]	30.00	0.0	.329	35.400	0.000	.060B/.06PB1.7/S/30
[illegible]	30.60	0.0	.470	40.732	-1.268	.060B/.06PB1.7/S/30
[illegible]	29.40	0.0	.600	48.082	1.082	.060B/.06PB1.7/S/30
12	29.40	24.9	.020	36.486	1.086	.060B/.06PB1.7/S/30
12	30.20	15.7	.189	70.646	6.446	.060B/.06PB1.7/S/30
12	30.00	18.9	.329	89.384	.284	.060B/.06PB1.7/S/30
12	30.60	19.7	.470	104.690	-5.810	.060B/.06PB1.7/S/30
12	30.00	19.0	.600	124.300	0.000	.060B/.06PB1.7/S/30
13	29.00	0.0	.020	10.098	.898	.06MB/.06PB1.7/S/30
13	29.40	0.0	.189	15.339	.639	.06MB/.06PB1.7/S/30
13	29.40	0.0	.329	20.192	.892	.06MB/.06PB1.7/S/30
13	29.50	0.0	.470	28.602	.702	.06MB/.06PB1.7/S/30
13	29.00	0.0	.600	35.616	1.316	.06MB/.06PB1.7/S/30
13	29.00	20.5	.020	19.629	3.029	.06MB/.06PB1.7/S/30
13	29.40	15.9	.189	37.216	4.516	.06MB/.06PB1.7/S/30
13	29.40	17.6	.329	54.920	4.420	.06MB/.06PB1.7/S/30
13	30.00	19.0	.470	68.490	0.000	.06MB/.06PB1.7/S/30
13	29.00	20.5	.600	81.666	3.066	.06MB/.06PB1.7/S/30
14	29.80	0.0	.020	11.113	.213	.06MB/.06PB.5/S/30
14	30.50	0.0	.189	9.927	-.373	.06MB/.06PB.5/S/30
14	30.40	0.0	.329	16.573	-.527	.06MB/.06PB.5/S/30
14	30.30	0.0	.470	21.569	-.331	.06MB/.06PB.5/S/30
14	29.80	0.0	.600	26.603	.203	.06MB/.06PB.5/S/30
14	30.00	19.0	.020	20.330	0.000	.06MB/.06PB.5/S/30
14	30.00	19.0	.189	37.670	0.000	.06MB/.06PB.5/S/30
14	30.00	19.0	.329	50.400	0.000	.06MB/.06PB.5/S/30
14	30.00	19.0	.470	49.950	0.000	.06MB/.06PB.5/S/30
[illegible]	29.80	23.2	.600	58.304	-5.796	.06MB/.06PB.5/S/30